GEOLOGY
FOR ENGINEERS

GEOLOGY FOR ENGINEERS

By

BRIGADIER-GENERAL

R. F. SORSBIE

C.B., C.S.I., C.I.E.

Late Royal Engineers

LONDON

G. BELL & SONS LTD

1938

Printed in Great Britain by
NEILL & CO., LTD., EDINBURGH

PREFACE

THE first edition of this book was published in 1910. It has now been thoroughly revised and largely rewritten. The chapters devoted to Applied Geology have been considerably extended, and those devoted to Historical Geology have been omitted for want of space, while the chapter on Geological Observation—Indoor Work—has been omitted, as it is considered preferable for the Engineer to consult a professional chemist.

The tendency to specialise in 'watertight compartments' is perhaps still more highly developed now than in 1910, with the result that the bearing of geology in relation to almost every branch of engineering is very frequently neglected or ignored. A knowledge of geology is, however, of the first importance to the practical engineer, but it is difficult for him to study the application of this science to his requirements without having recourse to a large number of different text-books and other works. References to geology which may be of the greatest practical importance are often almost hidden away or treated in an obscure fashion, whereas the engineer requires the needful information to be put before him in a clear and concise manner. To meet this want I have endeavoured to compile the requisite information in one volume, in the hope that it may serve as a handy book of reference.

The late Professors Lapworth, Cole and Bauerman, and Mr Hayden of the Geological Survey of India gave me much kind help and encouragement in the preparation of the first edition, for which I am very grateful, and I am greatly indebted to the following authors and publishers for so kindly allowing me to take such extracts as I required from the books shown below and for permission to reproduce the figures mentioned.

Manual of Geology, Theoretical and Practical, by John Phillips, LL.D., F.R.S., Part I; *Physical Geology and Palæontology*, by H. G. Seeley, F.R.S. Charles Griffin & Co.; figures 8–17, 19–24.

Geology: Chemical, Physical, and Stratigraphical, Vol. I. *Chemical and Physical*, by Joseph Prestwich. Clarendon Press; figure 2.

The Principles of Waterworks Engineering, by J. H. T. Tudsbery, D.Sc., and A. W. Brightmore, D.Sc. Third Edition. E. & F. N. Spon; figure 40.

Sanitary Engineering, by Vernon Harcourt. Longmans, Green & Co.

Aids in Practical Geology, by G. A. J. Cole, M.R.I.A., F.G.S. Fourth Edition. Charles Griffin & Co.; figure 25.

Physical Geology, by Ralph Tate. The Technical Press Ltd.; figures 7, 18, and 26.

The Rudiments of Civil Engineering, by H. Law. The Technical Press Ltd.

The Study of Rocks, by Frank Rutley, F.G.S. Longmans, Green & Co. Sixth Edition.

Economic Geology, by David Page, LL.D., F.G.S. Wm. Blackwood & Sons.

Calcareous Cements, by G. R. Redgrave and Charles Spackman. Charles Griffin & Co. 1905.

Limes, Cements, Mortars, etc., by G. R. Burnell. The Technical Press Ltd.

Road-making and Maintenance, by T. Aitken. Charles Griffin & Co.

The Construction of Roads, Paths, and Sea Defences, by Frank Latham, C.E. The Sanitary Publishing Co., Ltd.

Professor Mahon's 'Elementary Essay on Road-making,' quoted in *Rudiments of the Art of Constructing Roads*, by H. Law, C.E. Weale's Series. The Technical Press Ltd.

Pioneer Engineering, by E. Dobson. The Technical Press Ltd.; figures 41 and 42.

An article on 'Broken-stone Roads,' by Reginald Ryves, in *Engineering*, 1905, pp. 76 and 205.

Tidal Rivers, by W. H. Wheeler, M.I.C.E. Longmans, Green & Co.

An article on 'Coast Erosion and Reclamation,' in *The Engineer* of 27th April 1906, and subsequent numbers.

Coast Erosion and Foreshore Protection, by J. S. Owens, M.D., A.M.I.C.E., F.R.G.S., and G. O. Case. St Bride's Press; figures 43–46.

Some of the books mentioned in the various Bibliographies at the end of Part I and of subsequent chapters, *e.g.* Humber's *Water Supply of Cities and Towns*; Ansted's *Elementary Geology*, etc. may be considered out of date, but they contain much valuable information on what I may term 'geological engineering,' which is, I believe, not to be found elsewhere.

R. F. SORSBIE

July 1938.

CONTENTS

INTRODUCTION

PART I

GENERAL PRINCIPLES

CHAPTER I

DYNAMICAL GEOLOGY

Section I. Changes on the Earth's Surface

Section II. Changes within the Earth

CHAPTER II

STRUCTURAL GEOLOGY

STRUCTURAL CHARACTERS OF ROCKS

Section I. Igneous Rocks

Section II. Aqueous Rocks

Section III. Metamorphic Rocks

CHAPTER III

MINERALS

Section I. The Study of Minerals

CHAPTER IV

THE STUDY OF ROCKS

The Term, Rock

Section I. Mode of Origin

Section II. Chemical and Minerological Composition

Section III. Structure

Section IV. Physical Characters

CHAPTER V

ROCKS

Section I. Igneous Rocks

Section II. Aqueous Rocks

Section III. Metamorphic Rocks

Section IV. Rock Decomposition

PART II

GEOLOGICAL OBSERVATION

CHAPTER VI

FIELD GEOLOGY

Section I. Geological Surveying

Section II. Structural Characters of Rocks

Section III. Determination of Rocks

PART III

APPLIED GEOLOGY

CHAPTER VII

WATER-SUPPLY

Section I. Rainfall and Evaporation

Section II. Underground and Surface Waters

Section III. Springs and Wells

Section IV. Rivers

Section V. Lakes and Impounding Reservoirs

Section VI. Quality of Water

CHAPTER VIII

BUILDING STONES

IMPORTANCE OF PRACTICAL KNOWLEDGE OF GEOLOGY

Section I. Igneous Rocks

Section II. Sandstones, Limestones, and Argillaceous Rocks

Section III. Weathering, Quarrying and Testing Stone

CHAPTER IX

BRICKS AND CLAYS

CHAPTER X

LIMES, CEMENTS, AND PLASTERS

CHAPTER XI

ROADS AND CANALS

Section I. Road Construction

Section II. Waterbound and Partially Waterproof Roads

Section V. Protective Measures

CHAPTER XIV

DRAINAGE AND RECLAMATION OF LANDS

Section I. Drainage of Lands

Section II. Reclamation of Lands

CHAPTER XV

SOILS AND SITES FOR BUILDINGS

Section I. Soils and Subsoils

Section II. Building Sites

LIST OF ILLUSTRATIONS

TABLES

INTRODUCTION

GEOLOGY is the science which investigates the physical history of the earth. It treats of the agents which produce changes on the earth's surface and within it, and seeks to determine the manner in which the evolution of the earth's great surface features has been effected. It deals with the materials which form the solid framework of the globe, and in these, together with the remains and records of past life, finds the data for geological history.

Practical Uses. That a knowledge of this science must be a great advantage to engineers will be obvious to all who study their profession, and especially to those employed abroad, who often must win from Nature the materials with which they may eventually defy her destructive efforts.

The following are some of the practical uses of a knowledge of geology :—

Hydraulic Engineering. The engineer has to provide and distribute supplies of water for domestic use and for power. He has to direct and control the natural flow of surface-waters by drainage and river regulation. He has to construct canals, harbours, docks, and piers.

All these works constitute the great branch of our profession called *hydraulic engineering*, and in all of them a knowledge of geology is indispensable.

For *water supplies* the engineer must study the geological structure and formation of the area in order to find suitable sites for wells, and to ascertain whether artesian wells are possible ; the nature of the rocks in the gathering grounds of reservoirs and rivers will greatly affect his calculations, and faults and fissures must be studied in this connection. *River regulation* and *canal construction* cannot be adequately treated without a knowledge of geology. The *drainage* and *reclamation of lands* are likewise largely dependent on geological factors. *Docks*, *harbours*, and *piers* cannot be efficiently constructed without a knowledge of coast erosion, which depends largely on geology.

Building. Geology affords indispensable information as to the stratigraphical position, availability, composition, durability, and

weathering properties of rocks, which afford materials such as building stone, clay for bricks and tiles, lime and cement, etc.

Road-making. Geology is of great importance in guiding the engineer as to (1) the choice of a line of road, so as to prevent slipping and ensure proper drainage; (2) what rocks are obtainable and suitable for road metal.

Earthwork. For the engineer making tunnels, cuttings, and embankments, foundations for bridges, or constructing canals and docks, it is most necessary that he should know (1) the character of the rocks met with, especially whether hard or soft, and whether permeable or not to water; (2) the succession of strata in the district and their thickness; (3) the dip of the strata and the direction of the drainage.

Branches of Geology. The chief branches of Geology with which the engineer is concerned are:

(1) Dynamical Geology, relating to the causes of change in the earth's crust.
(2) Structural Geology, relating to the structure of rock-masses.
(3) Petrological Geology, relating to the origin, occurrence, and structure of the constituents of the earth's crust.
(4) Historical Geology, relating to the chronological order of strata and the succession of forms of life.

Arrangement Adopted. Branches (1), (2), and (3) are dealt with in Part I of this book in a somewhat sketchy manner, which however, it is hoped, may be found sufficient to enable the engineer to follow the chapters on Applied Geology. But for further study of these branches, as well as for branch (4), Historical Geology, which is omitted altogether for want of space, the engineer is referred to standard text-books.

In Part II such geological observation as can be made out of doors is briefly described, but for indoor work reference to an expert is necessary.

Part III contains a résumé of Applied Geology under the heads of Water Supply, Building Stones, Bricks and Clays, Limes and Cements, Roads, Rivers, Coast Erosion, Soils and Sites for Buildings, Drainage and Reclamation.

PART I

GENERAL PRINCIPLES

CHAPTER I

DYNAMICAL GEOLOGY

Dynamical Geology is the study of the agencies which have produced geological changes, their laws and modes of action.

The ultimate source of all geological energy both inside the earth and on its surface is, so far as we know at present, the sun.

SECTION I. CHANGES ON THE EARTH'S SURFACE

The **Agencies** which effect changes on the surface of the earth are *air*, *water*, and *life*. In the text-books their action is considered separately, but the engineer must remember that the work of the various agencies is so intimately connected that it is often impossible to say that the effects produced, whether destructive, transportive, or constructive, are due to any one of them.

Denudation is the process by which the surface of the ground is broken up and its ruins carried away, so as to lay bare new surfaces.

Weathering includes all those changes which occur as a result of the action of heat and cold, rain, hail, snow, wind, exposure to air, and other atmospheric and chemical processes in rocks and other substances.

As weathering is of great importance to the engineer, it is described more fully in Chapter V, Section IV.

WORK OF THE ATMOSPHERE

Changes of Temperature cause rocks to split, and this action is accelerated when the rocks contain moisture. The agency of the **wind** as a denuding power is easily underestimated—it abrades rocks to such an extent that at times they become shaped like mushrooms or gigantic clubs; it lowers the level of the land, and in dry countries forms thick deposits, as in Central Asia. The formation of *loess* has been ascribed to the action of the wind. It is an exceedingly fine yellowish, powdery unbedded loam, and is frequently calcareous. *Sand-drift* is sand driven and accumulated by the wind. *Sand-dunes* are low hills which at times advance as much as 60 feet per annum under the action of the wind.

Rain acts both mechanically and chemically. It acts *mechanically* by washing away loose materials. Its *chemical action* depends chiefly upon the substances which it abstracts from the air, and produces the following changes: (a) *Oxidation*—forming a thin oxidised layer on the surface of rocks, which sinks in if not washed off at once; (b) *Deoxidation*—organic particles taken up by rain will reduce peroxides to protoxides; (c) *Solution*—by the mere action of water, *e.g.* rock-salt, or by the carbonic acid present; (d) *Formation of carbonates*—*e.g.* lime dissolved by carbonic acid may be redeposited when the water evaporates, and felspars may be decomposed; (e) *Hydration*—some rocks will absorb water and become disrupted, *e.g.* anhydrite into gypsum.

The **Formation of Soil and Subsoil** is due to a variety of processes, of which the chemical action of rain is perhaps the most important.

The rock-surface is broken up by the weathering processes referred to above, as well as by the action of vegetation. If the ground is level or concave, soil is formed *in situ* (see fig. 1), but if convex, the disintegrated material is carried down by the rain into the hollows, or washed away by streams to be deposited in pools, lakes, or oceans, and eventually form new rocks. It may thus leave *earth pillars* when a large block of conglomerate, etc., or stone protects the soil from disintegration; and by washing off the soil on higher ground it exposes fresh surfaces to disintegration, and the process of soil manufacture is thus continually renewed.

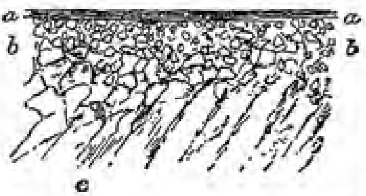

FIG. 1. Rocks passing up into soil.

Rain accumulates material on the slopes below steep cliffs, forming what is called a *talus*.

Screes are long trails of loose blocks collected on the slopes beneath precipitous mountain-sides.

Rain-wash is the name given to accumulations of soil, often mixed with angular fragments of rock, which are washed down into the hollows, and often furnish brick-earths.

WORK OF UNDERGROUND WATER

Source. A large portion of the rain which falls on the land sinks into the ground and is lost to sight. The remainder is either

evaporated or flows off into streams and rivers, and eventually most of it finds its way into the sea (see *Work of Running Water* below).

Most soils and rocks are more or less porous, and the harder rocks are usually so broken by joints and fissures that water easily penetrates to a considerable depth. The greatest depth reached may be assumed to be about six miles.

Springs are due to the intervention of impervious strata which hold up the water and enable it to reappear at the surface. See Chapter VII, in which both springs and wells are dealt with.

Amount of Underground Water. This depends on the following :—

(1) *Amount of rainfall.*

(2) *Rate of rainfall.* The heavier the fall the less water sinks into the ground, as the surface soon becomes waterlogged.

(3) *Formation of the surface.* The flatter the ground, the more water will sink in ; the steeper the slope, the quicker the water runs off.

(4) *Texture of the soil.*

(5) *Texture* and *structure of the underlying rock.* Stratified rock is usually more favourable for the entrance of water than massive rock.

Chemical Action. Just as the chemical action of rain produces changes such as oxidation, formation of carbonates, hydration, etc., so underground water may produce changes analogous to weathering, which are often intensified by internal heat and pressure. The *subtraction* of soluble matter from rock renders it porous. The *substitution* of certain mineral substances for others extracted from the rock is frequently effected. In districts containing rocks which are easily soluble, *subterranean channels* and *caverns* are often found. In calcareous districts, vertical cavities called *swallow-holes* or *sinks* may be formed. *Stalactites* and *Stalagmites* are due to the action of underground water.

Landslips are common in volcanic districts. The chief agent, however, is water, which most commonly acts by insinuating itself into minute cracks which are widened and deepened by frost. When the fissure becomes sufficiently deep, on the melting of the ice a landslip occurs. Sometimes when the strata are very much inclined and rest on an impermeable bed like clay, the water which percolates through the more porous rocks above, softens the clay, which becomes slippery, and the superincumbent mass slides over it to a lower level.

Work of Running Water

Source. A large proportion of the rain which falls on the earth is carried off at once by a vast natural drainage system, which forms a network over the land. Passing rapidly from the higher ground by streams and brooks into rivers, which eventually find their way into the sea, the running water carries with it a large amount of material in the shape of mechanical sediment, or in solution, the major portion of which is deposited in the lower levels (see *Deposition* below), though some finds its way into the sea.

Brooks and rivers would cease to flow in dry weather but for the fact that they are fed by springs which originate as described above, and in greater detail in Chapter VII; also by mist, dew, and melted snow.

The **Work** done by running water is chiefly mechanical, and may be subdivided into (1) erosion, (2) transportation, and (3) deposition; but these are interdependent. Erosion is increased and accelerated by the amount of sediment transported, and deposition depends on the rate of transportation as well as on the amount of sediment carried.

The mineral matter carried in solution by running water is derived from rain passing over rocks or from springs. It increases the mechanical action, but is not of great importance otherwise.

Erosion. The *gravel rolled along the bed* of a stream serves as a tool to excavate the channel. The *matter carried in suspension* also has an excavating and erosive effect. The *rate of erosion* depends on (i) the nature of the channel, (ii) the rock formation, (iii) the climate.

(i) *Nature of Channel.* The greater the slope the more rapid is the rate of erosion, both in the channel of a stream and in the basin which it drains. In places where an eddy occurs and there is a gravelly bottom, the circular motion of the gravel excavates *pot-holes* or depressions in the river bottom.

(ii) *Rock formation.* The rate of erosion is dependent on both the structural and petrological characters of the rock (see Chapter IV). Stratified and jointed rocks, or those possessing cleavage properties (see Chapter II, Section III), like slate, are more easily eroded than massive rocks, and fine-grained, compact rocks resist erosion much better than those which cohere loosely.

Angular fragments have far more eroding effect than the rounded fragments afforded by conglomerates, etc.

If the rock is soluble it will be easily eroded; but if the cementing

material of the rock is soluble while the harder portions remain undissolved, the rock will be an efficient eroding agent.

(iii) *Climate.* The most important factor in promoting erosion is rain, and, where conditions are favourable to weathering, the rate of erosion will be more rapid than where but little weathering takes place.

The **Transportation** effected by a stream depends on (i) transporting power of the current, (ii) accessibility of materials, (iii) chemical composition of the water.

(i) *Transporting power* depends on the velocity, and varies as the sixth power of the velocity. The *velocity* of a stream depends chiefly on its gradient, its volume, and the amount of sediment it moves, the latter absorbing a certain amount of energy which reduces the velocity. The velocity of a current is greatest in the centre of a river and least at its borders. In ordinary cases the least, mean, and greatest velocities may be taken as bearing to each other nearly the proportion of 3, 4, and 5.

The following are the effects in the removal and transport of various materials by currents of given velocities acting on the bed of a river :—

Soft clay requires a velocity of . . .	0·25 feet per second
Fine sand " " . . .	0·50 " "
Coarse sand and gravel as large as peas require a velocity of	0·70 " "
Gravel as large as French beans requires a velocity of	1·00 " "
Gravel of pebbles 1 inch diameter requires a velocity of	2·25 " "
Pebbles $1\frac{1}{2}$ inch diameter require a velocity of	3·33 " "
Heavy shingle requires a velocity of .	4·00 " "
Soft rock, brick, earthenware require a velocity of	4·50 " "
Larger blocks of rock require a velocity of	6·00 " " and upwards

(ii) *Materials.* The average specific gravity of the materials varies from two to three times that of water, and consequently, when stones, etc., are carried along by the water, they lose from one-half to one-third their weight in air, and thus large blocks are easily carried along.

Coarse materials such as small stones, gravel, and coarse grains of sand are rolled along the bottoms of streams, but finer particles of

matter are held in suspension, although their specific gravity is greater than water, by subordinate upward or rotatory currents which are set in motion by obstacles such as boulders, or by different velocities in different parts of the stream which exert different pressure on the sides of the particles in suspension.

(iii) *Chemical composition.* Water chemically impure contains a considerable amount of mineral matter in solution, which reduces its transporting capacity below that of pure water.

Deposition takes place when the velocity of a stream is checked. The sediment thus deposited is called *alluvium.* Deposits usually occur under the following conditions :—

(*a*) Where the gradient is suddenly decreased, *alluvial fans* or *cones* are formed.

(*b*) Where the gradient is gradually reduced, deposits will form slowly, covering the flood plains of streams and forming *alluvial plains.*

(*c*) In these alluvial plains or flats, owing to the gentle current, there is a tendency to *meander,* and both deposition and erosion take place at the same time, alluvium being deposited on the concave side of each bend, while the bank is undercut on the convex side, the sinuosities being thereby gradually increased. Sudden floods, however, will often form short cuts, eliminating the bends, and they will also carry away some of the alluvium previously deposited, making the bed deeper, and leaving part of the old bed high and dry. *River terraces* are formed in this way (see Chapter XII, Section I).

(*d*) Where rivers and streams reach the sea, and the tides are low, *deltas* occur which spread out to sea. Strong tides and coastwise currents prevent the formation of deltas.

(*e*) Similar action occurs in *lakes,* which get gradually filled up with alluvium. Rivers also give rise to lakes, either by obstructing their tributaries by deposition at the junction of the latter, or, when the tributaries contribute more sediment than the main stream can carry, the latter drops part of its load and forms a bar which dams up the main stream and forms a lake.

(*f*) *Bars* are formed at the mouths of tidal rivers by the deposition of alluvium, due to the oscillation between the river- and sea-water.

Work of Frost, Snow, and Ice

Frost assists weathering and accelerates landslips. It acts with great intensity at high levels and in high latitudes, but even in

temperate regions its action is very marked and productive of great disintegration of rocks. Indeed, in the production of weathered crusts of rocks, frost is hardly less active than rain. Frost will split stone full of 'quarry sap' (*cf.* Chapter VII, Section II, 'Saturation,' etc.; Chapter VIII, Section I, 'Quarrying,' and Section III, 'Seasoning') if it is brought to the surface in winter.

Snow and Ice. *Snow* often causes floods by temporarily blocking up valleys. It protects the surface of the ground from the action of frost.

Above the *snow-line* there is a continual process of accumulation of snow, which presses downwards and converts the lower portion of the accumulated mass into ice, forming *ice-sheets*. The continual pressure from above gradually forces the ice to escape downwards by any available outlets. On the steeper slopes great masses of snow break away in the form of *avalanches*, which sweep down rocks and trees on steep hillsides, and on the gentler slopes *glaciers*, which are in effect rivers of ice, are formed. The motion resembles that of a river, quicker in the middle than at the sides and bottom. *Crevasses* are large cracks which are caused by the strains set up by the movement of the glacier. They extend across the glacier in curves, which are convex towards its source and are often very deep.

The work done by glaciers is similar to that done by running water, and includes erosion, transportation, and deposition.

Rocks subjected to glaciation are distinguished by scratches all in one direction, where they have scraped along the bottom.

FIG. 2. Roches moutonnées.

Erratic blocks are large stones carried down to lower levels by the ice, and are called *perched blocks* when they are left in precarious situations. Rounded masses of glaciated rock are sometimes called *roches moutonnées* (fig. 2), from their resemblance to reclining sheep.

Fluvio-glacial drifts consist of the angular fragments transported by the ice, mixed with the more or less water-worn drifts transported by the *glacier river* which issues from an ice-tunnel at the end of the glacier.

The broken-up rock and clays that accumulate under a glacier or sheet of ice, as well as all the drift that is deposited beneath the advancing ice, constitute what is termed *boulder-clay* or *till* or *ground-moraine*.

THE WORK OF THE SEA

Processes. Those portions of the earth's crust which are covered by seas are affected by the same three processes as the actual land surfaces, viz.:

(1) Crust movements or *diastrophism*.
(2) Volcanic action or *vulcanism*.
(3) *Gradation*.

Of these the first two processes are discussed in Section II.

Gradation. On land, degradation predominates and aggradation is less important, but in the sea aggradation is far more important than degradation. The degrading or denuding action of the sea is termed *marine denudation* to distinguish it from subaerial denudation, and though the sudden destruction caused by the sea often appears great, it is in reality of less geological importance than the gradual action of subaerial denuding agents.

The gradational processes at work in the sea are greatest near its shores. They are chiefly mechanical, by movements of the water, but also chemical, due to precipitation of solution, and organic, *e.g.* corals, shells, and carbonaceous matter producing deposition.

Movements of the Water (see Chapter XIII). These are actuated by (1) tides, (2) wind, (3) differences of level due to influences exterior to the surface of the earth, (4) volcanic disturbances or other earth movements. These all tend to produce (*a*) waves, or (*b*) sea-currents.

Wave-action. Waves are caused by (*a*) tides, (*b*) wind, (*c*) volcanic disturbances; but their action is similar in each case, the difference being only as regards their intensity. Tidal waves are usually increased by wind. When passing through narrow straits the tide becomes a current and may be an effective agent of erosion.

The highest part of the wave is called the *crest*, the lowest the *trough*; the distance from crest to crest or from trough to trough is called the *length* of the wave, and the vertical height of the crest above the trough is the *height* or *amplitude*.

When waves flow in on a shelving beach the velocity of the

undulation diminishes, the troughs become flatter and the crests higher. At length the crest begins to curl over, and finally it topples as a *breaker* upon the shore.

The water carried forward by waves recedes along the bottom and forms the *under-tow*. When the wave is oblique to the shore an *alongshore current* is produced, but the under-tow remains at right angles to the shore.

Sea-currents. The effect of *oceanic* currents is not of much importance, since they do not touch bottom, but in places where they are forced through narrow and shallow passages they have considerable abrading effect.

Many coast-lines are, however, swept by currents that hug the shore and run in one direction during the whole or greater part of the year. These *alongshore* or *littoral currents* may be termed rivers of sea-water, and, like freshwater rivers, they are important agents of transport and erosion (see Chapter XIII, Section III).

Erosion. *Chemical action.* The free carbonic acid in sea-water dissolves all kinds of calcareous rocks and attacks felspar in igneous rocks. The free oxygen continues the disintegration by oxidising the iron-bearing minerals. *Mechanical action.* The action of the sea on a coast (see Chapter XIII) is chiefly of an auxiliary nature in that its principal work is to pulverize and dispose of material brought down from the cliffs or on the shore by atmospheric agency, but it has a direct action between low- and high-water levels. The downward effective range of wave-action is very limited, and submarine structures are little disturbed at 15 to 25 feet below the surface.

Erosion is effected both by the waves themselves and by the detritus carried by them. The waves, armed with the loose material which falls from above, cut like a saw and will often undercut cliffs, especially where a hard rock above high-water level overlies softer rock (see fig. 3). As the undercutting continues, large rocks and boulders fall from above, which are soon reduced to smaller dimensions, and in their turn reinforce the waves in their eroding action.

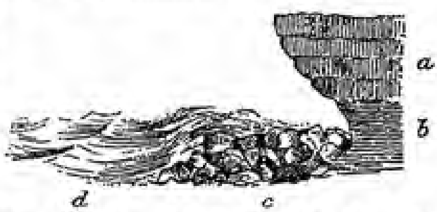

FIG. 3. Action of sea on rocks of coast. *a*, hard rock; *b*, soft rock; *c*, fallen rock; *d*, sea.

The *abrading power* of waves depends not only on the relative

hardness of the rocks of which the coast is composed, but also on the position of the beds, and on the planes of cleavage and of joints (see Chapters II and IV).

Some rocks, such as slate, stand the effect of waves very well. Limestone, on the other hand, gets much eroded by the action of carbonic acid in sea-water.

The power of the waves is often very great (see Chapter XIII, Section III, *re* 'Breakers').

If the earth's crust had remained stationary and no uplift had taken place, marine erosion, combined with the erosive action of other agents, would have produced a level plain covered by the sea. Such a plain is termed a *plain of marine denudation*, or *base level of erosion*; and geological history tells us that many such plains have been formed and subsequently uplifted, becoming some of the great plains of the earth.

Transportation and Deposition. The eroded material is carried away by the action of the waves, under-tow, and shore currents, which keep the sediment in transit and gradually sift it so that the coarsest materials accumulate when there is most agitation, and the finer parts remain in suspension or are deposited in calmer water.

Alongshore currents produce what is termed *littoral drift* (*cf.* Chapter XIII, Section II), *i.e.* the travel of loose material parallel to the shore. This material may be deposited on headlands or in estuaries. Littoral drift usually follows the direction of the tides.

Incoming waves bring material to the shore and the under-tow carries out detritus; hence where the waves break, ridges or barriers are formed which may increase until they enclose lagoons, and eventually the latter become filled with sediment. Deposition usually takes place opposite the mouth of a bay, owing to the shore current being checked in the deeper water of the bay.

Oceanic Deposits. These consist of (a) *Pelagic* deposits formed in deep water remote from land, and (b) *Terrigenous* deposits formed in water close to land.

Pelagic deposits consist of the following deep-sea deposits: (1) Red clay, (2) Radiolarian ooze, (3) Diatom ooze, (4) Globigerina ooze, (5) Pteropod ooze.

Terrigenous deposits are divided into (*a*) Deep-sea deposits known as *Hemipelagic*, and extending from the 100-fathom line to where terrigenous merge into pelagic deposits, and comprise (6) Blue mud, (7) Red mud, (8) Green mud, (9) Volcanic mud, and (10) Coral mud.

(*b*) Shallow-water or *Thalassic* deposits found between the 100-fathom line and low-water mark, and consisting of sands, gravels, muds, etc.

(*c*) *Littoral deposits*, consisting of boulders, gravels, sands, and other coarse materials derived from the land (see Chapter XIII, Section II).

The Work of Living Organisms

Vegetable. The roots of *plants* and *trees* open up the subsoil to the action of air and water, and may even split rocks. The roots or branches of sand-loving plants protect loose soil or sand from removal by the wind. Moisture-loving plants keep the surfaces of rocks moist and thus promote decay. Lime-secreting plants encrust rocks on shores of seas and lakes and form sheets of limestone. The decay of plants furnishes strong acids which aid the action of water on rocks and minerals and add to the soil. Seaweeds often break the force of the waves or lessen the effects of the ground-swell. Peat-mosses and mangrove and other swamps are accumulations of plant growth.

Vegetation often checks erosion by forming a sort of carpet of turf, etc., which protects the surface of the land. *Woods* and *forests* attract rain, and so increase the action due to rain and running water (see above). Moist wood is slowly converted by decay into a brown substance called *Humus*, and forms the chief part of the organic matter in soils; the *regur* or *black cotton soil* of India is formed from decayed vegetation; and *bog-iron ore* is formed by the action of decayed vegetation on iron.

Siliceous or flinty vegetable accumulations take place in fresh water through the growth and decay of *diatoms*, which also form extended deposits in the ocean.

Animal. *Burrowing animals* expose the soil to denudation. Dams made by beavers often alter watercourses. Marine-boring shells pierce limestone and promote its decay. *Decaying animal matter* adds to the effect of *decaying vegetable matter* in promoting the disintegration of rocks. *Limestone* is chiefly formed from animal remains, and *coral reefs* are built by living organisms. *Man* interferes with the action of Nature in many and various ways: affecting meteorological conditions by removing and planting forests, interfering with the action of subaerial and subterranean agencies by drainage, agriculture, controlling rivers, and engineering

operations for water supply, mines, etc.; and by his presence in large numbers adds to the soil in towns.

SECTION II. CHANGES WITHIN THE EARTH

The levelling tendency of the external agencies is continually opposed and counteracted by internal agencies. These are (1) Volcanic action or Vulcanism, and (2) Movements of the earth or Diastrophism, which include (*a*) the sudden *earthquake*, and (*b*) the slow, long-continued *crust movement*. All of these are actuated by certain forces within the earth.

Volcanoes

The explosive action of volcanoes is due to heated water and gases generated near the surface either by radioactivity or other causes. The permanent records of volcanic action are (1) volcanic products, (2) volcanic vents.

(1) **Volcanic Products.** The ejected materials are not only spread out round the volcanic crater, but are often carried to considerable distances. They may be solid, liquid, or gaseous. The steam and gases which are the first products of an eruption carry with them dust as well as coarser materials, but of themselves leave scarcely any lasting mark. The gases may, however, act chemically upon the neighbouring rocks, or produce deposits of sulphur or other minerals.

The gases, etc., are followed by *fragmentary materials*, and after the shower of these has subsided, molten *lava* wells up from the interior of the volcano.

Lava consists of molten or half-molten rocky material containing a large quantity of water, which escapes from it in the state of steam, filling the upper portion of the lava stream with bubbles, and rendering it light and full of *vesicles* (*i.e.* small spherical or bubble-shaped cavities). The vesicles are elongated by the motion of the lava stream, and as the heat escapes by radiation, a crust is formed which may be broken up into *scoriæ* or cellular fragments resembling cinders. This crust checks the escape of heat, but the upper portion of the lava stream, owing to radiation through the cracks and vesicles and conduction through the thin layer of the upper portion, cools far more rapidly than the central and lower portions. The rapid cooling is unfavourable to the formation of crystals, and the texture of the rocks becomes glassy (vitreous) or stony (lithoid) and cryptocrystalline.

The vitreous or glassy form of acid[1] lavas is called *obsidian*, or simply *volcanic glass*; and the black glassy form of basic[1] lavas *tachylyte*. *Pumice* is a highly vesicular light, spongy glass, formed on the surface of acid lavas and frequently fibrous. It is really a cindery form of obsidian.

Fragmentary materials consist of blocks, bombs, lapilli, scoriæ, ash, and dust. The blocks are often very large and generally more or less angular; when consolidated they form *volcanic breccia*. *Lapilli* are small stones varying in size from that of a pea to a walnut.

The finer material ejected from volcanoes is frequently subjected to wind sorting, and hence is at times deposited in layers which often possess a stratified appearance. Such bedded material is called *volcanic tuff*.

(2) **Volcanic Vents.** All the time that the eruption is in progress the volcano undergoes changes in form, partly from the accumulation of ejected materials on its flanks, partly from the building up of new lateral cones upon it. But more important changes are developed at the top of the mountain; for, as the superheated water rises towards the surface, and flashes into steam in the throat, its explosive force blows out the loose materials of which the cone was composed; and thus the mountain becomes truncated, and its conical upward termination is often replaced by a funnel-shaped pit, which does not always become entirely obliterated by subsequent eruption.

Crust Movements

Sea-level Changes. The sedimentary rocks which constitute the main mass of the land either have been elevated to their present position, or the sea has been lowered. In which latter case the sea, which must have been lowered over its whole area, must have been reduced in depth equal to the height of some of the highest mountains. But the quantity of water on the earth remains the same; hence, if the sea-level changes, such change must arise from the formation of hollows in the crust of the earth, the filling up of its deeper parts, or by the contraction of its capacity by the rising of the solid rock.

Evidences of oscillation of level are met with in the occurrence

[1] When the silica is in excess of the bases—iron, alumina, lime, potash, and soda—the rock is said to be *acid* or *acidic*; where the percentage of silica is low, the rock is said to be *basic*.

of *sea-beaches* now far removed from the action of the sea, *sunken rocks*, and *submerged forests*, and such movements are indicated by accurate measurements referred to some standard of level which has not been disturbed.

Alterations of land levels, by elevation or depression, which are found in different parts of the world, are the effects of subterranean movements, and are of two kinds:

(1) Secular, or movements progressing slowly.

(2) Paroxysmal, taking place suddenly, and which are intimately connected with earthquakes (see below).

Secular movements may be local or widespread. In the former case they are due to chemical changes in the rocks or minerals, whether by solution of rocks such as rock-salt, limestone, or gypsum, or of some of the constituents of rocks such as granite, basalt, etc., or by hydration or carbonation (*cf.* Section I). Widespread movements may be due to loss of the internal heat of the earth by radiation, causing shrinking and crumpling of the earth's crust.

Earthquakes

Earthquakes are closely connected with the crust movements above described. They occur most frequently where folding and faulting are of recent origin, but are sometimes the result of volcanic action, and often precede or accompany eruptions. They may also be due to settlement in regions of less than average density, or where the roofs of underground hollows collapse.

Earthquakes are more frequent near the sea than far from it, and are common among many of the great mountain ranges of the world.

The **geological effect** of earthquakes is not so great as might be supposed. They sometimes cause a permanent elevation or depression of the land, as well as landslips and rents of the ground. Indirectly they may produce derangements of lakes, rivers, and springs.

Changes in Rocks

Causes. The forces—heat, water, and pressure—which set in motion the larger earth movements have also a considerable effect on the actual rocks.

Heat. Not only does the original heat of the globe, as well as the heat due to the transformation of mechanical energy in the crushing and crumpling of rocks, act upon the rocks themselves,

but the heat due to chemical changes within the earth's crust must also be taken into account. Rocks expand on fusion and contract on solidification.

Water. All rocks contain water within their pores, which is known as *interstitial* water, and the minute cavities in crystals are usually filled with water. This water usually contains other matters in solution, and thus has a powerful chemical effect which is greatly enhanced by heat.

Pressure acts (1) vertically, producing consolidation; (2) laterally, producing or tending to produce metamorphism; and (3) as a heat producer.

Effects. These forces produce the following results:—

Structural characters, such as joints, folds or plications, faults, foliation, cleavage, etc., are established (see Chapter II).

Metamorphism, or a total change of condition in rocks, such that their original characteristics have become disguised or wholly obliterated (see Chapter II, Section III).

CHAPTER II

STRUCTURAL GEOLOGY

Structural Character of Rocks. The method of building up the component parts of rocks, known as the *structure* or *texture*, is described in Chapter IV, Section III. In this chapter we are concerned with Structural Geology, which deals with the larger structural features of rock-masses.

From the structural point of view rocks may be *massive*, *i.e.* compact and homogeneous; *bedded* or *stratified*; or *foliated*, *i.e.* with division planes imposed by pressure. It will, however, be more convenient to consider the structural character of rocks according to their mode of origin, viz. *Igneous*, or generated by heat; *Aqueous*, or water-formed; and *Altered* and *Metamorphic*, or those which have undergone change.

Most igneous rocks are massive, but some aqueous rocks also have this characteristic. In some aqueous rocks the bedding planes are indistinguishable, while some igneous rocks are bedded. Many but not all altered and metamorphic rocks are foliated.

SECTION I. IGNEOUS ROCKS

These have all consolidated from a state of fusion. The majority are *massive* or *crystalline*, others are *fragmental*. The massive igneous rocks are generally completely crystalline, but a few are more or less vitreous, and some contain a certain amount of amorphous matter. The fragmental igneous rocks consist of volcanic ashes compacted more or less firmly.

Occurrence. The crystalline or massive varieties may occur either as *effusive* or volcanic rocks, *i.e.* lavas which have been ejected and then consolidated, or as *intrusive* rocks which have been injected from below into cracks and fissures in the strata, and cooled below superincumbent masses.

Again, intrusive rocks may be *plutonic* or *abyssal*, *i.e.* those which consolidated at considerable depth within the earth's crust, or they may be *hypabyssal* or *dyke* rocks, *i.e.* those filling cavities which have cooled more rapidly than plutonic rocks, but not

so rapidly as volcanic rocks. Hypabyssal rocks are sometimes known as 'Intrusive' rocks, but the latter term is more generally applied to both plutonic and hypabyssal rocks.

A plutonic rock may have exactly the same mineralogical composition as a volcanic rock, having issued from the same molten rock-mass, but owing to the different conditions under which it solidified it will differ in the following points :—

(1) It will contain no vesicular, slaggy, or glassy portions.
(2) It will generally be more coarsely and completely crystalline.
(3) It will not be stratified.
(4) The crystals will probably contain no water-cavities.

Effusive Rocks are either massive or crystalline lavas, fragmentary ashes, lapilli, etc.

The effusive rocks that issue from a volcanic vent (*cf.* Chapter I, Section II) usually form *streams* ; while those that issue from fissures may either form streams or may spread over the country in *sheets*, filling up inequalities of the ground as they do so.

The vesicles of ancient lavas are often filled by *amygdaloids* or almond-like inclusions, which frequently yield agates or zeolites.

The stratified ashes and tuffs are called *pyroclastic* sediments to distinguish them from aqueous sediments.

Intrusive Rocks are classified according to the nature of the cavity in which they have been consolidated, as follows :—

Necks or *Plugs* are volcanic chimneys which have been filled up with erupted material, and have been exposed at the surface by denudation.

Veins are strings of rock filling narrow, irregular crevices which often have many ramifications.

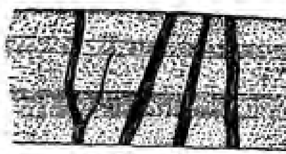

FIG. 4. Volcanic dykes. *a*, *b*, beds of volcanic ashes, etc.; *c*, *d*, *e*, *f*, solid walls or dykes of stone.

Dykes (fig. 4) are wall-like masses of rock filling regular-shaped fissures, more or less parallel-sided, and cutting across the planes of bedding. They are generally nearly vertical or highly inclined. Occasionally a dyke may be hollow, the lava having solidified only at the margin of the fissure.

Sills, or intrusive *sheets*, are bed-like masses which have been thrust between the planes of sedimentary or even igneous rocks.

Laccolites are cistern or cake-shaped masses, with a flat base, thinning out at the sides, which have consolidated in the space

where the overlying strata have been forced up into an arch or anticlinal.

Batholiths are conical masses which rise from great depths and eat into the strata lying above and around them. They have vertical margins.

Bysmalith is an intrusive mass in shape more like a plug or core, but rising from great depths and faulting the overlying beds instead of arching them. Its vertical dimensions are greater than its lateral ones.

Bosses or *Stocks* are the largest and most shapeless masses of extruded material. They include large bodies of granite which have risen through the sedimentary rocks and cover extensive areas, often many miles across. From their margins, veins, dykes, and strings run out into the surrounding rocks which have been altered by contact-metamorphism (see below).

Joints. 'When igneous rocks cool they contract, and thus fissures called "joints" appear in them. These joints run through

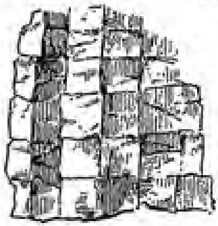

FIG. 5. Jointed structure of granite.

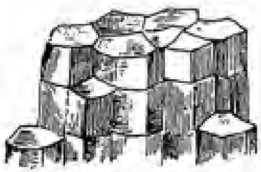

FIG. 6. Columnar structure of basalt.

the rock in different directions, according to its composition and the conditions under which it cooled; and at times the same rock presents two or three kinds of joints, or it shows no joints at all. In granite (see fig. 5) the prevalent joints run in straight lines, which cross each other at some angle; while in basalt (see fig. 6), phonolite, and some other rocks the joints often form hexagonal columns, which may be straight or curved, and vary from an inch or two in diameter up to a width of many feet.'[1]

SECTION II. AQUEOUS ROCKS

These have been **originally deposited** in water. Their particles are usually smoooth and rounded; they contain fossils and are generally stratified, though some aqueous rocks are unstratified and

[1] Phillips: *Manual of Geology*, Part I, H. G. Seeley, p. 42.

some igneous rocks are stratified (see above). As a rule they are derived from other rocks.

After deposition various **changes** occur.

1. They are consolidated and stratified.
2. The strata become inclined.
3. The strata are bent and sometimes inverted.
4. Joints are formed.
5. Fractures and movements cause dislocation.

(1) Consolidation and Stratification

The **Sediment** carried off by the action of wind and water, as described in Chapter I, is laid down in lake and river bottoms or the floor of the sea and consolidated into rocks, in regular layers, *strata*, or tabular masses of various thicknesses.

The sediments are at first in an incoherent condition, *e.g.* sands, clays, gravels, etc., but with few exceptions they gradually become indurated by the combined action of pressure, heat, and infiltrating water.

Stratified rocks are generally non-crystalline and fossiliferous, and the order of superposition is constant. This principle is our chief guide in tracing the geological formations.

Forms of Bedding. The thinnest separable layers or sheets in the planes of deposition are called *laminæ*. They may be parallel or oblique to the general stratification. They are generally found in fine-grained rocks.

The thicker layers are usually called *beds* or *strata*. Single beds may be as much as 200 feet thick, but the average thickness is about 5 feet. There may be as many as thirty or forty laminæ to the inch.

The lines of stratification must not be confused with those of lamination or of joints, cleavage, foliation, or flow-structure (see below).

The strata or beds, according to the conditions in which they were laid down or formed, may be: (1) Fluviatile (in river-beds); (2) Glacial; (3) Estuarine or Fluvio-marine (at the mouths of rivers); (4) Lacustrine (in lakes); (5) Marine; (6) Aeolian (formed by air).

False-bedding (fig. 7), also called *current-bedding*, *cross-bedding*, or *drift-bedding*, is due to changes in the directions of the currents which laid down the deposits, and is characterised by laminæ laid at various angles to the plane of the bed. It is a common feature

among coarse sandstones, giving them a rough, uneven surface and a tendency to oblique fracture.

While it is true that the strata, which cover extensive districts, follow one another in strictly chronological order, still they are by

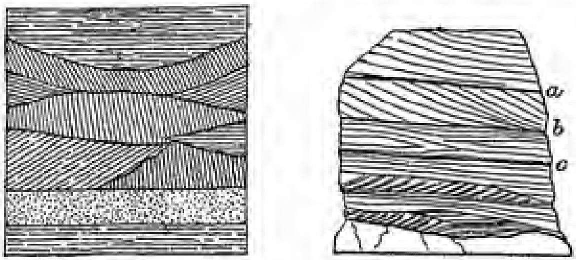

Fig. 7. False-bedding.

no means uniform. The different strata often thin out in places so that they assume a wedge-shaped or *lenticular* section, and occasionally, owing to local modifications, strata are interposed in places (fig. 8).

Character of Strata. Fine-grained deposits, such as limestone and shale, have a tendency to be more persistent and to cover larger areas than do conglomerates and sandstones. Certain varieties of rock are often associated together; thus fine-grained

Fig. 8. Lenticular, interposed, and divided beds.

Fig. 9. Alternation of beds.

sandstone occurs with shale, conglomerate with grit, limestone with fine shales, etc.

Moreover, individual beds may vary in different places. Conglomerate may pass into sandstone, sandstone into shale, and shale into limestone.

Alternation of Beds. When sets of strata are in contact—as, for instance, limestone lying upon sandstone—it often happens that while the limestone above and the sandstone below are unmixed with other matter, there is a middle class of beds composed of alternate layers of the sandstone and limestone. Thus in fig. 9

let *a* be Coralline Oolite and *b* Calcareous Sandstone; the middle beds *a'*, *a,"* *b,'* *b"* are alternately oolite and sandstone.

(II) Inclination

Dip and Strike. Where strata have been tilted their inclination referred to a horizontal plane is termed the *dip*. The amount of inclination, or angle of dip, is expressed in degrees and measured by a clinometer. The direction of the dip, which is always the steepest line of the inclined surface, is measured with a compass. To find the amount and direction of the dip, see Chapter VI.

The line of direction followed by an inclined bed in crossing the country is known as its *strike*. Strictly speaking, the strike is the *intersection of the plane of the surface of the inclined bed with a horizontal plane*. If a flat piece of cardboard is held in an inclined position in a trough of water, the horizontal line of intersection of the surface of the cardboard with the surface of the water answers to the line of *strike*; and a drop of water placed on the cardboard, in air, will run down the steepest line upon the card and mark the line of *dip*.

The direction of the strike is indicated by its compass bearing, and is always at right angles to the direction of the dip. The strike of a bed is usually more or less straight, but if the bed is bent or folded, the strike necessarily curves or changes from point to point.

The exposure at or above the surface of the ground of any stratum, vein, dyke, or deposit of rock is termed its **Outcrop.** The line of outcrop, or *basset edge*, is the line where the stratum, etc., cuts the surface of the ground. It is also known as the line where the bed 'comes to-day.' It corresponds with the boundary line of the overlying formation (*cf.* Chapter VI, Section I).

If the ground is level the direction of the outcrop of a bed coincides with its strike, but not otherwise. The breadth of the outcrop depends on the angular difference between the slope of the ground and the slope of the bed (*cf.* Chapter VI, Section II).

An **Outlier** is a portion of a stratum which has become separated from the principal mass by denudation, and remains isolated like an island. It is always newer than the formation around it (see figs. 10 and 11). An **Inlier** is an older deposit which is exposed by the removal of a portion of an overlying stratum, so that it lies within a girdle of the surface rock (see figs. 12 and 13).

Unconformability. When there is a break in the succession of

strata and the surface of the older strata becomes denuded, and the strata disturbed and inclined before the next strata are laid

FIG. 10. Section of outlier.

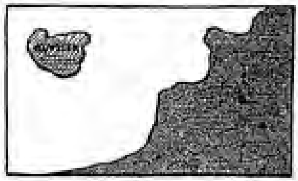

FIG. 11. Map of outlier.

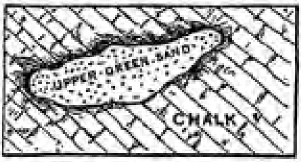

FIG. 12. Map of an inlier.

FIG. 13. Section of inlier.
A, Chalk; B, Upper Greensand.

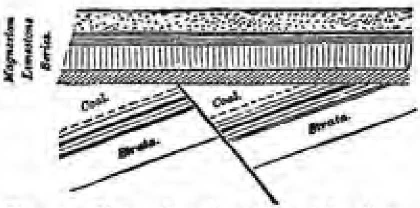

FIG. 14. Unconformity of stratification.

down, the new strata are said to rest *unconformably* on the old strata (see fig. 14).

Strata are sometimes conformable in one section, and yet, when traced to a distance, are found to be unconformable to the deposits on which they rest. This condition is termed *overlap* or *transgression*, because the overlying deposit extending beyond the beds previously deposited overlaps and covers them up (fig. 15).

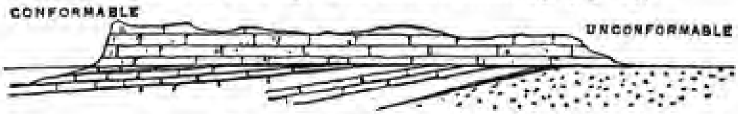

FIG. 15. Diagram of overlap.

(III) CURVATURE OR FLEXURE

Folds. Owing to the action of the forces referred to in Chapter I, Section II, strata frequently have been displaced from their hori-

zontal position and bent or folded in various directions. Dip is always part of a fold. When the strata are folded upwards into an arch, it is called an *anticline* or *saddle* (fig. 16). When the strata are folded downwards into a trough, it is called a *syncline* (fig. 17).

When the strata are bent from the normal direction for some

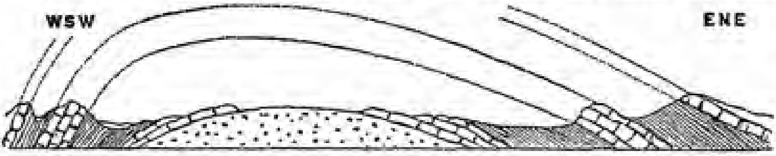

FIG. 16. Anticline.

FIG. 17. Syncline.

distance and then resume the original direction, it is called *Monoclinal* flexure.

If the beds dip away in all directions from a centre they are said to have a *periclinal* or *qua-qua-versal* dip, and the structure is called a *dome*. If they dip everywhere towards a centre they have a *centroclinal* dip, or form a *basin*.

Overthrust occurs when the upper or arch limb has been pushed over the lower or trough limb; *underthrust*, when the lower limb has been pushed under the upper one.

A turned-over fold is called an *overfold* or *inverted fold*. A succession of closed inverted folds forms an *isoclinal*. *Plication* is a form of minute folding, common among older rocks such as mica, schist, gneiss, etc. Rocks very strongly plicated are said to be *contorted*.

(IV.) JOINTS

All water-formed rocks, after being upheaved, dry and shrink. This shrinkage is not merely lateral, but to some extent vertical also, and these shrinkage planes are the beginnings of *joints*. Afterwards, when the strata become strained and bent during the changes of level in land, these planes become extended and systematised in definite directions.

In sedimentary rocks the joints traverse, as a rule, only a single

bed or stratum, fresh joints occurring in the strata above and below. There are usually one set of joints running with the strike and one set running with the dip, known as *strike joints* and *dip joints* respectively.

TABLE I. JOINTS

Rock	Nature of Joints
Laminated sandstones, shale, and some kinds of slate.	Very numerous and close.
Limestones	Less frequent and more open. Vertical joints generally regular.
Coarse sandstones . . .	Very irregular.
Clay	Vertical joints numerous, but small and confused.
Indurated shale	Very long, straight, and parallel.

Master Joints. Joints which keep the same direction for long distances and run through a considerable thickness of beds are called *master joints*.

(v.) DISLOCATION

Faults are the result of vertical movements by which whole masses of strata, either horizontal or inclined, being too rigid to bend under flexure, are dislocated so that on one side of the line of fracture the corresponding rocks are much higher than on the other. 'This difference of level in places sometimes amounts to hundreds or even thousands of yards. The succession of strata is on each side the same, their thickness and qualities are the same, and it seems impossible to doubt that they were once connected in continuous planes, and have been forcibly and violently broken asunder.'[1]

The actual plane of fracture and slipping along which the strata have given way is known as the *fault-plane*, and the line of outcrop of this plane of fracture upon the surface of the ground as the *fault-line*. That side of the fault-plane upon which the beds have been relatively depressed is known as the *downthrow* side and the opposite as the *upthrow* side. The *throw* is the perpendicular distance between the two portions of any dislocated stratum ($d\ b'$ in fig. 18).

Hade. 'The plane of separation between the elevated and depressed portions of the strata is sometimes vertical, but generally

[1] Phillips: *Manual of Geology*, Part I, H. G. Seeley, p. 76.

sloping a little. The direction of inclination of the plane of a fault is termed its *hade*, and is measured from the vertical ($c\ b\ f$ in fig. 18). In this case a peculiar general relation is observed between the inclination of this plane and the effect of the dislocation. In fig. 19, for instance, the plane of separation $z\ z$ slopes under the depressed and over the elevated portions of the disrupted strata, making the alternate outer angles $z\ z\ b$, $z'\ z'\ b'$ *acute*.

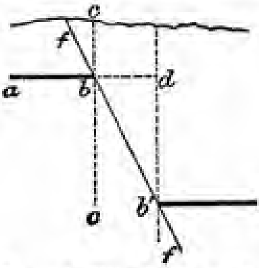

FIG. 18. Breadth and throw of a fault.

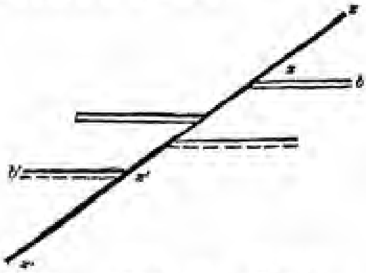

FIG. 19. Dislocation of strata.

'In several hundred examples of such dislocations which have come under notice an exception to this rule is rarely found. The *direction* of the hade is almost invariably *towards the down-throw.* A similar law is found to prevail very generally in the crossing of nearly vertical mineral veins; for instance, in fig. 20 $a\ a$ are two portions of a metallic vein dislocated by another vein $b\ b$. In this

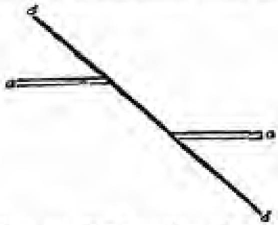

FIG. 20. Dislocation of vein.

FIG. 21. Reversed fault.

case the relation of the line $b\ b$ to the lines $a\ a$ is the same as that of $z\ z'$ to the lines $b\ b'$ in fig. 19.

'The contrary appearances, had they occurred, would have been as represented in fig. 21, and such occur in the mining district of Cornwall; they are termed *upthrow* or *reversed* faults. When faults are parallel to each other, and the throw is always in the same direction, the strata descend like steps, and the faults are

known as *step-faults.* When faults cross each other they produce the phenomena termed *trough-faults* or *cross-faults.*' [1]

Shift. The breadth or shift of a fault is the perpendicular distance between the planes perpendicular to the beds at their fractured ends (*b d* in fig. 18).

Fault-line. The line in which a fault extends is always sinuous, and, owing to displacement, faults always include many pockets in which minerals may accumulate. The line of dislocation is generally distinguished by a fissure which is filled by fragments of the neighbouring rocks or by basalt, and then is called a *dyke*, or by various sparry and metallic minerals, and is then called a *mineral vein.* The faulted surfaces which have been compressed against each other are hardened, striated, and often polished, when they are termed *slickensides.*

SECTION III. METAMORPHIC ROCKS

The older water-formed rocks have often undergone changes which have obliterated some of their original features which were due to deposition, and have imparted characters which at times make it difficult to discover that they were ever deposited in water. Thus clays have been changed into slates, sandstones into quartzite, and limestones into marble. Crystalline rocks, too, have been altered into schists and gneisses. Rocks so changed are known as *metamorphic rocks.*

Metamorphism consists in the alteration or destruction of the original structures, and the development of new minerals which are always crystalline in structure, while the chemical composition of the rocks suffers little change.

Foliation. In many metamorphic rocks the newly developed minerals have arranged or aggregated themselves in more or less parallel layers or *folia* that give rise to the structure called *foliated.* Foliated rocks generally split readily into thin plates or flags parallel with the foliation planes. Such rocks are called *schists.*

Thus metamorphic rocks may be massive or schistose, and may show all degrees of metamorphism from highly contorted granitoid gneissic schists to altered sediments in which the nature of the original sediments can be identified.

Kinds of Metamorphism. Two distinct kinds are recognised:

Contact metamorphism is developed around masses of igneous rock, especially when these have been intruded among sedimentary

[1] Phillips: *Manual of Geology*, Part I, H. G. Seeley, p. 77.

rocks in the form of large bosses of granite, etc. It occurs also in the case of dykes, but often with much less effect on the surrounding rocks, which may be only slightly baked or recrystallised for a few inches. The effect, however, is greater where there has been a prolonged flow of heated matter.

A great granite boss ten to twenty miles broad may be surrounded by an aureole of contact alteration as much as a couple of miles in width.

Regional metamorphism is so called because it affects large tracts of country. Where it occurs there is often much evidence of crust movement accompanied by folding and crushing. As compared with the characteristic diminishing intensity of contact metamorphism, the intensity of regional metamorphism is often nearly uniform over a large area.

Results of Metamorphic Action. These depend largely on the nature of the rocks involved. Clays may be altered into slates by pressure alone, while slates may be again altered by heat and pressure. Sandstones are less readily altered than shales or slates and limestones, especially if marly or argillaceous, are more easily altered than pure shales. Schists and gneisses, being already crystalline, are very resistant to heat. Igneous rocks, consisting as they do of minerals formed at high temperatures, may not be affected at all, but if decomposed, may be entirely recrystallised.

Principal changes effected. Limestone becomes crystalline or is converted into *marble*; impure limestone may lose its carbonate of lime and become *rottenstone*. Sandstone becomes *quartzite* or quartz schist. Clays become slates; lumps of clay embedded in the magma become *porcellanite*; slates, shales, and marly clays are sometimes converted into *lydian stone* or *hornstone*. Granite becomes gneiss. Open rock fissures become filled up by crystallised deposits of quartz, calc-spar, and other minerals, forming *mineral veins*.

Cleavage. In the case of rock-masses composed of homogeneous and comparatively soft material, crust-pressure frequently produces the structure called *cleavage*. 'This consists in a peculiar fissility of the rocks which are affected by it, parallel to a certain plane, which almost always cuts at a considerable angle the plane or curved surfaces of the stratification. In fig. 22, which represents a mass of rocks in which this definite quality of splitting is developed, B B is the surface (curved in this instance) of one bed of the stratification; J is on the plane, here supposed vertical of a

joint; C is one of the planes of cleavage, cutting the surface of stratification B B in *s s*. Parallel to this plane C, the mass of rock here represented is cleavable by art, and is often actually cleft by Nature into very thin and numerous plates which, when of suitable quality and reduced to proper size, constitute the roofing-slates of our European houses. The edges of these plates may be traced with care on the vertical surface of the joint J and the sloping surface of the bed B, and are represented in the figure by fine lines.

'It will be observed that these lines do not cross the bed marked *g*. This is supposed to be a hard grit or conglomerate, and such rocks are sometimes only in a slight degree affected by the cleavage which, however, is perfect above and below them in fine-grained and more argillaceous strata. Certain small joints, however, and numerous cleavage planes often cross sandstone beds, and then the cleavage and joint planes *in those beds* are not parallel to the general cleavage, but meet the surfaces of stratification as in fig. 22, at angles more nearly approaching to a right angle. At *l* the cleavage crosses nodular limestone or ironstone, and in these irregular layers becomes irregular, curved, and confused.

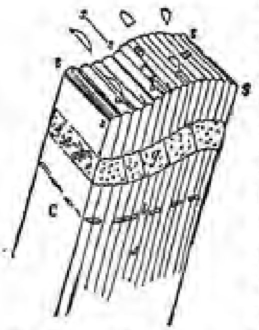

FIG. 22. Cleavage not passing through a bed of sandstone (*g*).

'On the surfaces of stratification the cleavage structure is frequently traced in narrow, interrupted hollows and ridges; these surfaces have in fact been folded, or plaited, or puckered by the force which occasioned the cleavage; and the little folds thus occasioned are traceable across shells, trilobites, etc., which are thus more or less distorted in the figure.

'*Stratification and Cleavage.* One general relation appears between the stratification and the cleavage—a relation arising from the displacement of the strata by axes of elevation and depression. Parallel to these axes is the "strike" or horizontal line on the surface of the strata; if this be taken on a great scale and the strike of the cleavage (similarly defined) be compared with it, the direction of each is found to be the same, or nearly so; in other words, the cleavage edges on the sur-

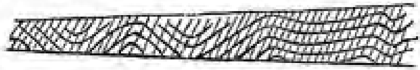

FIG. 23. Parallel cleavage in contorted strata of North Devon.

face of the strata are horizontal lines (*s s* in fig. 22). The *direction*, then, of the cleavage in a given district is dependent in a general sense on that of the axes of earth-flexure in that district; but the *inclination* of the cleavage has no necessary known relation to that of the strata (fig. 23); beyond this, that the dip of the strata being moderate, that of the cleavage is usually greater. In a country where the strata are much undulated, the cleavage may be, and mostly is, in parallel planes.' [1]

Joints. 'In slate districts, the joints, more numerous and more regular than in any other known rock, have almost universally a tendency to intersect one another at acute and obtuse angles, and thus to dissect whole mountains into a multitude of angular solids, with rhomboidal or triangular faces, which strongly impress upon the beholder the notion of an imperfect crystallisation, produced in these argillaceous rocks since their deposition and consolidation by some agency, such as heat or pressure, capable of partially or wholly obliterating the original marks of stratification; but we may with more probability here also appeal to tension in successively different directions as the true cause of these phenomena.' [2]

Relation between Igneous, Aqueous, and Metamorphic Rocks. 'The central cores of many volcanoes are found to be of granite; and when this rock cools more rapidly, as at the earth's surface under the pressure of the atmosphere, the minerals no longer form separately, but constitute rock consisting more or less obviously of a felspathic matrix in which crystals may occur. When poured out in a lava stream these rocks are called *felstones*, and when they assume a looser texture became scoriæ or ashes. If now we suppose the rocks over a central granite mass to become fractured

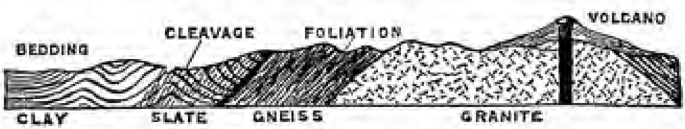

FIG. 24. Ideal section.

through their thickness so as to allow water to penetrate down to the heated mass and form a funnel or vent out of which the heated materials may escape, it is obvious that the central crystalline rocks will throw out lavas and ashes which may build up a volcano. Thus it follows that clay, slate, gneiss, granite, felstone, rhyolite,

[1] Phillips: *Manual of Geology*, Part I, H. G. Seeley, pp. 84–6.
[2] Phillips: *ibid.*, p. 82.

may all exist simultaneously as different conditions of the same rock, which have been produced in sequence to each other by the pressure which also brings mountains into existence, and changes the outlines of land and water. The ideal section (fig. 24) will illustrate the relations of the several kinds of rocks to each other, and show the order in which the several classes of rocks may succeed each other on the flanks of a mountain range.'[1]

[1] Phillips: *Manual of Geology*, Part I, H. G. Seeley, pp. 34–5.

CHAPTER III

MINERALS

THE terms *Petrology*, *Petrography*, and *Lithology* are frequently used indiscriminately to denote the study of rocks, but ' Lithology ' is now an obsolescent term, and ' Petrology ' more correctly denotes the study of rocks, treating of their origin, constitution, etc., while ' Petrography ' denotes the description and classification of rocks.

The engineer can best study the nature and effects of geological forces after he has acquired some knowledge of the constituents of the earth's crust.

SECTION I. THE STUDY OF MINERALS

The first mineral product met with in the examination of the solid portion of the earth is usually a loose *soil*, beneath which is a firmer material to which the term *rock* is applied.

On inspection the soil is found to be a mixture of fragments of substances of different kinds, and in most rocks the unaided eye is able to detect different kinds of matter. In granite, for instance, mere inspection shows us that there are at least three different kinds of matter, which are distinct from each other not only in outward appearance, but in all their manifold properties. It will be found, moreover, that by no amount of mechanical division can any of these three substances be reduced to others having different characters. They are therefore called *minerals*.

The **distinguishing characteristics** of minerals are:

1. Chemical composition.
2. Form.
3. Physical characters.

CHEMICAL COMPOSITION

It is desirable that the student of geology should have at least an elementary knowledge of chemistry, for which reference must be made to the text-books.

Elements. Their distribution in Nature is most irregular. Some are found in very large quantities and widely distributed, whilst others only occur in minute quantities in rare minerals.

The following are the *main elementary constituents* of the earth, forming about 97 per cent. of the earth's crust. The atomic weights are given, but do not give any idea of their relative importance as constituents of the earth:

Element	*Symbol*	*Atomic Weight*
Aluminium	Al	27·1
Calcium	Ca	40·07
Carbon	C	12·00
Hydrogen	H	1·008
Iron	Fe	55·84
Magnesium	Mg	24·32
Oxygen	O	16·00
Potassium	K	39·10
Silicon	Si	28·3
Sodium	Na	23·00
Sulphur	S	32·07

while the following are the most important of those present in small quantities:

Element	*Symbol*	*Atomic Weight*
Barium	Ba	137·37
Chlorine	Cl	35·46
Fluorine	F	19·00
Lithium	Li	6·94
Manganese	Mn	54·93
Phosphorus	P	31·04
Titanium	Ti	48·1

Sulphur and *carbon* are the only elements which commonly occur uncombined. The most important **compounds** are silica and alumina.

Aluminium (Al) occurs as an oxide called *alumina* or aluminium oxide (Al_2O_3). It is often found in union with silica, and forms the basis of many rocks and soils.

Calcium (Ca) forms a large proportion of rocks, occurring as calcium oxide or lime (CaO); as carbonate ($CaCO_3$) in limestone and chalk; as sulphate ($CaSO_4$) in anhydrite; as hydrosulphate in gypsum, selenite, and alabaster; and as fluoride in fluor-spar (CaF_2). It is an alkaline earth.

Carbon (C) in pure form occurs as *diamond* and *graphite*; in less pure form as *coal*; and combined with oxygen forms *carbonates*.

Hydrogen (H) chiefly concerns us as a constituent of *water* (H_2O) and many minerals.

Iron (Fe) is found chiefly in the form of oxides, carbonates, and sulphides. It is the principal colouring agent in rocks (see Chapter V, Section IV).

There are three oxides of iron :

Ferrous oxide (FeO) . . .	(Monoxide or protoxide).
Ferric oxide (Fe_2O_3) . . .	(Sesquioxide or peroxide).
Triferric tetroxide (Fe_3O_4) . .	(Magnetic oxide or ferroso-ferric oxide).

And iron may also exist in combination as FeO_3, forming *ferrates*.

Ferrous oxide is an unstable compound, and whenever it is produced is converted by the action of air into a higher oxide, a carbonate, or some other compound.

Ferric oxide and triferric tetroxide occur as minerals.

Magnesium (Mg) occurs widely diffused as carbonate in dolomite and magnesite ; as sulphate in Epsom-salt ; and as silicate in asbestos, talc, and steatite. Magnesium oxide or *magnesia* is used for firebricks, crucibles, etc. It is an alkaline earth.

Oxygen (O) is one of the chief constituents of the atmosphere, and constitutes nearly one-half by weight of the solid crust of the earth. It unites with nearly all elements.

Potassium (K) and **Sodium** (Na) are very widely distributed. Sodium is the more abundant, occurring as sodium chloride or common salt ($NaCl$) ; as sodium carbonate or common soda (Na_2CO_3) ; as nitrate of soda ; and as a silicate in felspar, etc.

Potassium is also found combined with chlorine, also with silica and alumina in felspar and mica.

Silicon (Si) is found in the form of oxide as *silica* (SiO_2), also called silicic acid and silicon dioxide, which constitutes a considerable portion of the earth's crust. Occurs in abundance as *quartz*, and also forms many silicates in combination with metallic bases.

Sulphur (S) occurs abundantly both free and in combination with oxygen and with other metals, forming sulphides, *e.g.* copper pyrites, galena, blende, etc., and sulphates, *e.g.* gypsum, anhydrite, and barytes.

Barium (Ba) is an alkaline earth ; **Chlorine** (Cl) and **Fluorine** (F) are halogens, combining with metals to form salts ; **Manganese** (Mn) is often found with iron among aqueous rocks ; **Phosphorus** (P) occurs combined with oxygen, chiefly in calcic phosphate ; the

commonest form of **Titanium** (Ti) is rutile or titanium dioxide (TiO_2), found associated with iron.

The chemical composition of a mineral can only be ascertained by exact analysis, which is beyond the scope of this book.

Mineral Forms

Mode of Occurrence. Minerals occur in two conditions:

(1) *Amorphous.* They are without any crystalline structure, they do not possess the property of cleavage (see Section III), and their physical properties are the same in every direction.

(2) *Crystalline.* They have a definite geometrical form, they possess the property of cleavage, and certain of their physical properties are directional, that is, they are not equally hard nor equally cleavable in all directions.

Many minerals which appear to be amorphous are really microcrystalline. The term *massive* is sometimes used as a synonym for 'amorphous,' but is also used for a crystalline mineral not showing crystal faces. Massive aggregates of crystalline material often occur, when their crystalline properties can only be detected with the aid of a microscope.

Amorphous minerals occur in the following states:—

(a) *Colloidal,* viz. resembling jelly or glue. The substance has no power to crystallise, and, if soluble in water, is held in solution very feebly and is easily precipitated. It is, however, often insoluble in water.

(b) *Glassy* or *vitreous.* More common in rocks than in minerals. The glass may consist of several minerals fused into one homogeneous substance. The same substance is capable of assuming both the crystalline and glassy state. Glassy bodies occasionally become stony by the formation of minute crystals within them; the glass is then said to be *devitrified.*

Physical Characters

Under this head we may group *physical characters* such as cleavage, structure, fracture, tenacity, hardness, touch, and specific gravity, as well as *optical properties* such as translucency, colour, streak, lustre, refraction, polarisation, pleochroism, fluorescence, etc., and also *thermal* and *electrical* properties. For most of the above the student is referred to text-books of mineralogy, but the

following notes may be of interest in connection with the subjoined list of minerals (see Section II).

Colour. In many cases, owing to the frequent admixture of foreign substances causing the same mineral to assume varying tints, colour cannot be regarded as a reliable criterion; but in the case of some minerals the characteristic colour is a valuable aid to identification, *e.g.* the green colour of chlorite, malachite, and glauconite; the copper-red of metallic copper; bronze-red and bronze-yellow of magnetic pyrites; brass-yellow of copper pyrites; lead-grey of galena; iron-black of magnetite and graphite.

Streak. The colour of the powder of a mineral, produced by drawing it over a file or a piece of unglazed porcelain, is a better guide than colour, as it is usually constant for the same mineral. The streak of metallic minerals is generally as dark, or darker, than the colour of the mineral; of non-metallic minerals, as light, or lighter, than the colour.

Lustre. This is the quality of the surface of a mineral, as regards the kind and intensity of the light it reflects. The chief **kinds** are:

Metallic, the brilliancy of polished metals, characteristic of native metals, and heavy metallic sulphides.

Adamantine, the brilliancy of the diamond.

Vitreous or *glassy*, characteristic of quartz, etc.

Resinous or *waxy*.

Fatty or *greasy*, the brilliancy of a freshly oiled reflecting surface, characteristic of slightly transparent minerals such as serpentine, nepheline, and sulphur.

Nacreous, like mother-of-pearl, characteristic of gypsum.

Silky, characteristic of fibrous aggregates, such as satin-spar.

Intensity of lustre is denoted by the terms *splendent*, *shining*, *glistening*, or *glimmering*, but these terms are used very loosely.

Fracture. The following terms are used to describe the surfaces of minerals broken in directions which are not cleavage-planes. As regards **form of surface**, minerals may be *conchoidal* (shell-like), having curved markings like those seen on the inside of many bivalve shells, as in flint and opal; *even*, a surface free from marked depressions or elevations; *uneven*, a surface having irregular depressions or elevations. As regards **nature of surface**, they may be *smooth*, as in lithomarge; *splintery*, as in serpentine and fibrous

hæmatite; *hackly*, or covered with sharp, wire-like points, as in native copper; *earthy*, when the mineral breaks like a piece of dried clay.

Tenacity includes (1) **Frangibility** or resistance to crushing. Minerals may be *tough*, or only broken with difficulty, as hornblende; *brittle*, or very easily broken with a blow, as tourmaline. Others are *friable* and *pulverulent*, or easily crushed between the fingers to a powder. (2) **Sectility**, or the property of being smoothly cut with a knife, as in the case of mica. (3) **Ductility**, or the property of being drawn out, as into wire or threads.

Malleability is the property of being hammered without breaking or cracking, *e.g.* gold, silver, copper, etc.

Rigidity. A substance is said to be *flexible* when a thin plate can be bent, and remains so without breaking, as talc; and *elastic* when, after being bent, it springs back to its original form.

Touch or **Feel**. *Soapy*, or unctuous, as talc and other magnesian minerals. *Meagre*, or moistureless: dry and rough to the touch, as chalk and magnesite. *Harsh*, or unpleasantly rough, as actinolite. Some minerals *adhere to the tongue*.

The **hardness** of minerals may be compared by trying to scratch them with a knife or file. *Mohs' scale of hardness* is as follows:—

1. Talc	6. Orthoclase
2. Selenite	7. Quartz
3. Calcite	8. Topaz
4. Fluor-spar	9. Sapphire
5. Apatite	10. Diamond

If a mineral will scratch talc with the same ease with which selenite scratches it, its hardness will be 1·5; if it only just scratches talc, its hardness will be 1·1 or 1·2; and if selenite only just scratches it, its hardness will be 1·8 or 1·9.

SECTION II. ROCK-FORMING MINERALS

These are described in alphabetical order of single minerals and important groups.

Abbreviations. *Col.* = colour ; *Str.* = streak ; *H.* = hardness ; *Fr.* = fracture ; *Ten.* = tenacity ; *Lus.* = lustre; *Feel.* = feeling to the touch.

Actinolite. See *Amphibole Group.*

Adularia. See *Felspars.*

Alabaster. See *Gypsum.*

Albite. See *Felspars.*

Amphibole Group. An important group, often known as the Hornblende Group. Amphiboles are similar to pyroxenes, but lighter.

Hornblende (Amphibole). *Col.*, green, brown, or black. *Str.*, grey. *Lus.*, vitreous, pearly, or silky. *Fr.*, subconchoidal, uneven. *Ten.*, rather brittle. *H.*, 5–6. A common constituent of many igneous rocks such as granites, syenite, diorite, gabbro, andesite, peridotite; more rarely in dark traps and basalts; also occurs in metamorphic rocks, *e.g.* gneiss, hornblende-schist, and amphibolite.

Actinolite resembles hornblende. *Col.*, bright green to grey. Occurs in crystalline schists and greenstones.

Tremolite. *Col.*, usually white or grey. Occurs in crystalline limestones and dolomites, and in igneous rocks.

Anatase. *Col.*, indigo blue, yellow brown, rarely colourless. *Str.*, white. *Lus.*, adamantine to metallic. *H.*, 5·5 to 6.

Andalusite. *Col.*, white, grey, reddish brown, olive green, or violet. *Str.*, white or colourless. *Lus.*, vitreous. *Fr.*, uneven, splintery. *Ten.*, brittle. *H.*, 7·5. Occurs in altered clay-slates, crystalline and mica-schists, also in gneiss and granite.

Andesine. See *Felspars.*

Anhydrite (Anhydrous Calcium Sulphate). *Col.*, usually white, sometimes greyish, reddish, or bluish. *Str.*, white. *Lus.*, vitreous or pearly. *Fr.*, uneven or splintery. *H.*, 3–3·5. *Distinguished* by hardness greater than gypsum, does not split into laminæ like gypsum. Occurs essentially associated with rock-salt and generally with gypsum. When exposed to the air for a long period it becomes partially hydrated or changes into gypsum. Also found in limestone rocks and in cavities with basalt.

Anorthite. See *Felspars.*

Apatite (Phosphate of Lime). *Col.*, variable, bluish green and greenish yellow, or colourless, also pink, violet, blue, or grey. *Lus.*, vitreous or resinous. *Fr.*, conchoidal. *H.*, 4·5–5. Occurs in veins or irregular crystals in crystalline limestones. A frequent accessory mineral in igneous rocks.

Aragonite. *Col.*, colourless, white, pale yellow, or tinted. *Lus.*, vitreous. *Fr.*, conchoidal, uneven. *H.*, 3·5–4. *Distinguished* by being harder than calcite as a rule. Occurs in hollows and druses in marls, limestones, basalts, and in veins in iron ore, etc.

Asphalt (Bitumen). *Col.* and *Lus.*, black, and lustrous like pitch. *Fr.*, conchoidal, sometimes vesicular. *H.*, 2. A number of natural inflammable pitchy or oily substances are included under the general term asphalt or bitumen.

Augite. See *Pyroxene Group.*

Barytes (Heavy-spar). A common vein mineral.

Biotite. See *Micas and Talcs.*

Bitter-spar. See *Dolomite.*

Bitumen. See *Asphalt.*

Bog or Brown Iron Ore. See *Iron*: Limonite.

Bog Manganese Ore. See *Manganese.*

Bronzite. See *Pyroxenes*: Enstatite.

Brown-spar. See *Calcite Group*: Dolomite.

Calcite Group. Carbonates of calcium, magnesium, and ferrous iron.

> **Calcite.** *Col.*, colourless or white, or tinted grey, red, green, blue, yellow, etc. Also when impure, brown or black. *Lus.*, vitreous to earthy. *H.*, 3. One of the most common and widely distributed minerals.
>
> **Dolomite** (Bitter-spar). *Col.*, usually pink, may be colourless, white, grey, green, brown, or black. *Lus.*, vitreous. *H.*, 3·5–4. *Pearl-spar* or *brown-spar* is a dolomite containing some iron, which is usually light grey or white, turning brown on exposure to air, pearly lustre. Abundant in mineral veins, also in rock-masses of magnesian limestone.
>
> **Magnesite.** *Col.*, white, yellow, grey, or brown. *H.*, 3·5–4·5. Associated with serpentine rocks, dolomite, etc.

Cawk. A white massive variety of barytes, used for adulterating white lead.

Celestite (Strontium Sulphate). *Col.*, colourless, white or pale blue, sometimes reddish. *Lus.*, vitreous or pearly. *H.*, 3–3·5. Found principally in marls and limestones.

Chalcedony. See *Silica Series.*

Chalcopyrite. See *Copper Pyrites.*

China Clay. See *Kaolin.*

Chlorite. See *Micas and Talcs.*

Copper Pyrites (Yellow Copper Ore, Chalcopyrite). *Col.*, brass to gold-yellow. *Str.*, greenish black, shining. *Lus.*, submetallic. *Fr.*, conchoidal to uneven. *H.*, 3·5. The standard ore of most copper-mining districts, occasionally met with in rocks such as diabase, granite, gneiss, argillaceous schists, etc.

Diallage. See *Pyroxene Group.*

Diopside. See *Augite.*

Dolomite. See *Calcite Group.*

Enstatite. See *Pyroxene Group.*

Epidote. *Col.*, yellowish to oil-green, brownish grey or black. *Lus.*, vitreous. *H.*, 6–7. *Ten.*, brittle. Occurs in many granites, and in crystalline schists and dolerites and other lavas.

Felspars are the most abundant minerals in igneous rocks. They can be just scratched with a knife, being softer than quartz, harder than apatite, and much harder than carbonate of lime. The colour is often milky white, sometimes bright red owing to oxides of iron, and occasionally grey or black or even green. *Str.*, usually white. *Lus.*, vitreous to pearly. *H.*, 6–6·5. They are classed as potash, soda, or lime felspars, and into Orthoclase and Plagioclase Groups—orthoclase being the typical potash felspar and the remainder plagioclase. They are also divided into *Monoclinic* and *Triclinic*, according to crystal formation.

Adularia. A white or colourless variety of orthoclase.

Albite. The typical soda felspar. Occurrence similar to orthoclase.

Andesine. Similar to orthoclase.

Anorthite. The typical lime felspar. Occurs in dark-coloured basic igneous rocks, *e.g.* lavas, diorite, etc.

Labradorite. Similar to andesine. Usually associated with pyroxenes and amphibole.

Microcline. Similar to orthoclase, but triclinic.

Oligoclase. Commonest form of soda felspar. Occurs as a constituent of igneous rocks, either as the sole felspar or associated with orthoclase and albite, as in granite, or with labradorite in basalt and dolerite.

Orthoclase (Potash Felspar). One of the commonest minerals. Occurs in igneous, aqueous, and metamorphic rocks. *Sanidine*, a glassy variety, often much cracked.

Fluor-spar (Fluor, Fluorite). *Col.*, very variable, rarely colourless and transparent, generally pale green, bluish green, yellow, or purple, or even deep blue, pink, or rose. *Str.*, white. *Lus.*, vitreous. *Fr.*, subconchoidal or splintery. *H.*, 4. *Distinguished* from calcite by superior hardness. Common as a vein or gangue mineral, and in limestone, dolomite, and altered rocks.

Glauconite (Greensand). A silicate of alumina, iron, etc. Usually impure, amorphous or earthy, yellowish to dark green, opaque, granular.

Gypsum. *Col.*, colourless or white, or tinted grey, yellow, reddish, or brown. *Lus.*, vitreous, nacreous, or silky. *H.*, 1·5–2. *Ten.*, flexible in thin laminæ. The crystalline variety, found in crystals or foliated masses, is often called *selenite.* Fibrous varieties, when the fibres have a silky lustre, are called *satin-spar.* *Rock gypsum* is massive, granular, or earthy, and often impure. The softness of all varieties of gypsum is characteristic. Common, and often interstratified with limestones or shales or underlying rock-salt.

Hæmatite. See *Iron.*

Halite. Common salt (NaCl). Colourless or white; when impure, yellow, red, blue, or purple shades. Transparent to translucent. *H.*, 2·5. Readily soluble in water. In crystals or granular crystalline, in masses known as *rock-salt,* also massive.

Hornblende. See *Amphibole Group.*

Hypersthene. See *Pyroxene Group.*

Ilmenite. See *Iron.*

Iron. Found chiefly in form of oxides, carbonates, and sulphides.

- **Hæmatite.** An oxide. *Col.*, bluish iron-black in crystals, various shades of brown and bronze-red in fibrous, earthy varieties. *Str.*, light to dark indian red. *Lus.*, metallic to dull. *Fr.*, conchoidal to uneven. *Ten.*, brittle. *H.*, 5·5–6·5. Common hæmatite and red hæmatite are massive and generally fibrous. *Specular iron ore* is hard, brilliant, and usually crystallised. *Reddle, Ruddle,* or *Red Ochre* is a light red earthy hæmatite generally mixed with clay.
- **Ilmenite** (Titanic Iron Ore). An oxide. *Col.*, black to brown, or dark grey. *Str.*, black to brownish red. *Lus.*, semi-metallic. *Fr.*, conchoidal, uneven. *H.*, 5·5–6. A common constituent of crystalline and igneous rocks.
- **Limonite** (Brown Hæmatite, Brown Iron Ore, Bog Iron Ore). *Col.*, brown in all shades. *Str.*, yellowish brown. *Lus.*, silky, resinous, or dull. *H.*, 5–5·5. *Ochre, umber,* and *Sienna earth* are mixtures of limonite and clay.
- **Magnetite** (Magnetic Iron Ore). An oxide. *Col.*, black. *Str.*,

black. *Lus.*, metallic. *Fr.*, conchoidal or granular. *Ten.*, rather brittle. *H.*, 6. Strongly magnetic. Occurs in immense beds and masses enclosed in gneisses and schists, also as accessory mineral in all kinds of rocks.

Siderite (Spathic Iron Ore, Chalybite). A carbonate; a common vein mineral.

Iron Pyrites (Sulphides). A general term for the following, as well as others which do not concern us.

Pyrite. *Col.*, brass-yellow to brown. *Str.*, greenish or brownish black. *Lus.*, metallic, splendent. *Fr.*, conchoidal. *Ten.*, brittle. *H.*, 6–6·5. The most abundant of metallic sulphides. An accessory mineral in igneous and sedimentary rocks.

Marcasite. *Col.*, pale yellow. *Str.*, greyish black. Readily decomposed on exposure to atmosphere. Occurs often as concretions in chalk.

Kaolin (China Clay). *Col.*, white or tinted. *Lus.*, usually dull. *Feel.*, unctuous. *H.*, 2–2·5. The basis of all clays.

Labradorite. See *Felspars.*

Limonite. See *Iron.*

Magnesite. See *Calcite Group.*

Magnetite. See *Iron.*

Manganese. *Col.*, usually black, but also brown, reddish, or green. The most common colouring ingredient of rocks, sands, and gravels. Varieties are *Pyrolusite*, soft manganese ore; *Manganite*, grey oxide; *Psilomelane*, hard manganese ore; and *Wad*, bog manganese ore.

Micas and Talcs. These include many species possessing the characteristic of dividing into thin laminæ which are sometimes more or less transparent. Both are tough and flexible, but mica is elastic, while talc is non-elastic. Mica is harder than talc, and gives a clean sensation when touched, while talc gives a greasy one. Talc and the white micas have a pearly lustre, while the dark micas have a submetallic lustre.

Biotite (Ferromagnesian or Black Mica). *Col.*, dark tints from brown through bottle-green to black. *Lus.*, splendent. *H.*, 2·5–3. Occurs in granites, gneiss, and schists, associated with muscovite. Common in dyke-rocks.

Muscovite (Potash or White Mica). *Col.*, colourless, grey, light green, or brown. *H.*, 2–2·5. The white mica of granite, syenite, gneiss, etc. Crystals may be exceedingly fine, or measure several feet across.

Phlogopite (Magnesian Mica). *Col.*, yellowish or reddish

brown, green or white. *Lus.*, vitreous to pearly. *H.*, 2·5–3. Occurs as a product of metamorphism in crystalline magnesian limestones and dolomitic marbles.

Talc (Steatite, Soapstone). *Col.*, generally pale green, sometimes grey or silvery white. Compact varieties dark grey or green. *Ten.*, sectile and flexible. *H.*, talc 1, steatite up to 2·5. Talc occurs crystallised and in schistose masses; steatite or soapstone in veins, nodular masses, or bedded deposits.

Chlorite. The name of a group—*Pennine*, *Clinochlore*, *Ripidolite*, etc. *Col.*, yellow-green to blue-green. *Lus.*, vitreous to pearly. *Ten.*, laminæ flexible but not elastic. *H.*, 2–2·5. Occurs in chlorite slate, protogene gneiss, diabase, etc.

Microcline. See *Felspars.*

Muscovite. See *Micas and Talcs.*

Nepheline. When massive, called *Elæolite.* *Col.*, colourless, white, or yellowish (Nepheline); grey, green, or reddish (Elæolite). *Lus.*, (Nepheline) glassy, (Elæolite) greasy. *H.*, 5·5–6. Occurs in igneous rocks and lavas.

Ochre. See *Iron.*

Oligoclase. See *Felspars.*

Olivine. *Col.*, olive to greyish green, brown. *Str.*, white. *Fr.*, conchoidal. *H.*, 6·5–7. Common in basalt, dolerite, and similar lavas.

Opal. See *Silica Series.*

Orthoclase. See *Felspars.*

Pearl-spar. See *Calcite Group.*

Pennine. See *Micas and Talcs*: Chlorite.

Phlogopite. See *Micas and Talcs.*

Psilomelane. See *Manganese.*

Pyrite. See *Iron Pyrites.*

Pyrolusite. See *Manganese.*

Pyroxene Group. Next to Felspars, Pyroxenes are the commonest constituents of igneous rocks; also occur in crystalline lime-stones, etc.

Augite. *Col.*, aluminous varieties are brown or black; non-aluminous, white, grey, or green. *Str.*, white or grey. *Lus.*, vitreous to pearly. *H.*, 5–6. Aluminous varieties occur in most metamorphic rocks, non-aluminous in basic igneous rocks, *e.g.* andesite, diabase, basalt, dolerite, etc. *Diopside*, a greyish or greenish white to pearl-grey and leek-green variety of augite.

Diallage. An altered form of *Augite* or *Diopside*. *Col.*, greyish green, dark green, or brown *Lus.*, pearly to metallic. *H.*, 4. Essential to gabbros; also in peridotite and serpentine, and occasionally in basalt and crystalline schists.

Enstatite. *Col.*, white, greenish, or brown. *Lus.*, slightly pearly. Occurs in irregular masses in plutonic rocks, in serpentine and also in volcanic rocks. *Bronzite* is a variety with metallic sheen, occurring in similar rocks and in crystalline schists.

Hypersthene. *Col.*, brownish white. *H.*, 6.

Quartz. See *Silica Series.*

Red Ochre. See *Iron*: Hæmatite.

Ripidolite. See *Micas and Talcs*: Chlorite.

Rock-salt. See *Halite.*

Ruddle. See *Iron*: Hæmatite.

Rutile. *Col.*, red, reddish brown to black. *Lus.*, adamantine to submetallic. *H.*, 6–6·5. Occurs in granite, gneiss, mica-schist, metamorphic limestone, dolomite, and quartz.

Satin-spar. See *Gypsum.*

Schorl. See *Tourmaline.*

Selenite. See *Gypsum.*

Serpentine. *Col.*, olive to blackish green, yellow, or white, often variegated. *Lus.*, greasy in massive varieties, silky in fibrous. *H.*, 2·5–5—usually 4. Found in both igneous and metamorphic rocks.

Siderite. See *Iron.*

Sienna Earth. See *Iron*: Limonite.

Silica Series. Silica in its various forms is the most abundant of all minerals.

Quartz. *Col.*, colourless, pale grey, pale or golden yellow, brown or red. *Lus.*, vitreous. *Fr.*, conchoidal, parallel, splintery in crystals of lamellar structure. *H.*, 7. An important constituent of the acid igneous rocks, *e.g.* granite, rhyolite, etc., and of metamorphic rocks, *e.g.* gneiss and mica-schist. It is an accessory component of many other rocks, and the mass of all quartzites and sandstones. *Chalcedony* is a mixture of quartz and amorphous hydrated silica, with a waxy lustre. *Common opal* has a vitreous to resinous lustre, and *H.* 5·5–6·5. Both are found in cavities in igneous and sedimentary rocks.

Hornstone or *Chert*, *Lydian-stone*, *Quartzite*, and *Flint* are chiefly composed of silica (see Chapter V).

Spathic Iron Ore and **Specular Iron Ore.** See *Iron.*

Sphalerite. See *Zinc-blende.*

Sphene. *Col.*, green, yellow, or brown—rarely red. *Lus.*, adamantine, vitreous. *H.*, 5–5·5. Occurs in granite, crystalline schists, limestone, etc.

Steatite. See *Micas and Talcs.*

Sulphur. *Col.*, sulphur-yellow, varying with impurities to yellowish green, grey, and red. *Lus.*, resinous. *H.*, 1·5–2·5. Found associated with gypsum, as an alteration product of a sulphate, or in connection with volcanic action.

Talc. See *Micas and Talcs.*

Titanic Iron Ore. See *Iron*: Ilmenite.

Tourmaline (Schorl). *Col.*, sometimes colourless, usually black. May be green, brown, blue, or even red. *Fr.*, conchoidal, uneven. *H.*, 7–7·5. Occurs in granite, gneiss, and crystalline schists.

Tremolite. See *Amphibole Group.*

Umber. See *Iron*: Limonite.

Zeolites. *Col.*, milky white, some reddish. *H.*, 3·5–6. Occur filling cracks and hollows among lavas or other minerals.

Zinc-blende (Sphalerite). *Col.*, usually yellow, brown, or black; compact varieties lighter. *Str.*, white. *Lus.*, adamantine or resinous. *Ten.*, brittle. *H.*, 3·5–4. A very common mineral, chiefly in veins in limestone rocks.

Zircon. *Col.*, brown or colourless, grey, green, or red. *Str.*, uncoloured. *Lus.*, adamantine. *H.*, 7·5. An accessory mineral of all kinds of igneous rocks, especially granite, syenite, diorite, etc.

CHAPTER IV

THE STUDY OF ROCKS

THE term **Rock** is applied to any bed, layer, or mass of the earth's crust, whether consolidated or not, not excluding beds of clay and sand. A rock may consist of one mineral species, as limestone, or of several intermingled, as granite. The minerals may be either loose, incoherent grains, *e.g.* blown sand, or coherent crystals or grains, angular or rounded, cemented by crystalline or amorphous matter. The usual cement is either silica, felspathic matter, carbonate of lime, carbonate of iron, or peroxide of iron.

SECTION I. MODE OF ORIGIN

The outer portion of the lithosphere, to a depth of perhaps 20,000 to 30,000 feet, is sometimes called the *zone of fracture*, and is acted on by the dynamical agencies, described in Chapter I, to such an extent that the rocks of which it is composed are in a constant state of change. The original rocky crust has been broken up into *mantle rock*, and its constituents have been dissolved or transported by running water until sedimentation has set in and sedimentary rocks have been formed. These *derived rocks* are, in their turn, again acted upon by the same agencies, and disaggregated.

IGNEOUS ROCKS

Origin. While it is practically certain that aqueous rocks are derived from igneous rocks, and that altered and metamorphic rocks are derived from both aqueous and igneous rocks, it is likely that the real origin of igneous rocks will always remain in doubt.

It is thought by some that igneous rocks show signs of derivation from aqueous rocks, and that all lavas are derived from aqueous rocks which have been subjected to intense heat and pressure until melted.

With such questions as these the engineer is not directly concerned, and it is of far more importance to him to study the wearing and weathering qualities of a rock and its liability to decomposition (see Chapter V, Section IV).

It is sufficient therefore to say that the same molten rock-mass or *magma* may issue as an effusive lava or an intrusive dyke, sill, or boss, and may form a different kind of rock according to the situation in which it was cooled and consolidated.

Aqueous Rocks

Ever since the surface of the earth was divided into land and sea a process of denudation (see Chapter I) has gone on, by means of which material has been obtained to form deposits in seas and lakes. Owing to the progressive shrinkage and consequent crumpling of the earth's surface, many of these deposits have been raised above sea-level, forming fresh deposits which, in their turn, were subjected to denudation, thus obtaining material to form newer deposits. This action is still going on, the older formations providing material for newer ones.

It has been found that the outer shell of the earth is chiefly composed of *stratified* rocks (see Chapter II) which are mostly of the following varieties:—

Arenaceous or sand rocks are typically fragmented or *clastic* in character—viz. composed of grains, derived from the waste of igneous rocks, held together by a cement or base.

Argillaceous or clay rocks similarly consist of derived elements held together by a fine-textured base or paste, and retaining enough moisture to be plastic.

Calcareous or lime rocks are chiefly of organic origin.

Metamorphic Rocks

The mode of origin of these rocks has already been described in Chapter II, but some of the chief effects of metamorphism may be noted here.

Igneous rocks are frequently altered by **thermal**[1] **metamorphism,** the principal changes being the replacement of one or more minerals by others in the vicinity of the region of thermal activity, *e.g.* intruded granite. The acid[2] rocks are less liable to thermal metamorphism than the intermediate[2] and basic[2] rocks.

In *Arenaceous* rocks the effects of thermal metamorphism depend on the nature of the deposits. A pure quartz sandstone or quartzose grit will be changed into a homogeneous quartzite, while if the original rock was impure and contained other substances, silicates

[1] The result of heat by which rocks are baked, hardened, and crystallised.

[2] See Section II: *Groups*.

of alumina, garnet, micas, etc., may be produced and the rock may assume a gneissose character.

Among *Argillaceous* rocks, clays are altered into slates and shales, and, when more highly metamorphosed, the whole body of the rock becomes altered into schists or compact masses like hornstone.

Calcareous rocks are altered into marbles and crystalline limestones, etc.

SECTION II. CHEMICAL AND MINERALOGICAL COMPOSITION

The percentage chemical composition of a fragment of rock depends on the chemical composition of the various mineral and chemical substances of which the rock is composed, and is only of service in so far as it affords an indication of the nature of the various substances.

The mineralogical composition is of great importance to the engineer, to enable him to ascertain the comparative durability of his materials.

General Terms. The following terms are used to denote the composition of rocks :—

Felspathic, consisting of, containing, or resembling felspar.

Siliceous, composed of or containing silica.

Quartzose, composed of or containing quartz.

Gypseous, having the properties of or containing gypsum.

Pyritous, having the property of one of the native metallic sulphides known as pyrites, though the term is often restricted to iron pyrites.

Carbonaceous, pertaining to or yielding carbon.

Saliferous, containing a considerable proportion of salt in beds.

Micaceous, composed of or containing layers or flakes of mica.

Igneous Rocks

The magma or ground-mass is invariably composed of silica, combined with the bases iron, alumina, lime, potash, and soda. When the silica is in excess of the bases, the rock is said to be *acid* or *acidic* ; when the precentage of silica is low, the rock is said to be *basic*.

Groups. Igneous rocks may therefore be divided into groups, according to their percentage of silica, as follows :—

Acid group with 65 to 80 per cent. of silica. Sp. gr., below 2·75. Granites, rhyolites, felsites.

Intermediate group with 55 to 70 per cent. of silica. Sp. gr., 2·70–2·80. Syenites, diorites, trachytes, andesites, porphyrites.

Basic group with 45 to 60 per cent. of silica. Sp. gr., 2·80–3·00. Gabbros, dolerites, basalts.

Ultra-basic group with 35 to 50 per cent. of silica. Sp. gr., 2·85–3·4. Peridotites.

The **Acid** group is distinguished by the presence of free silica or quartz in more or less abundance. The chief felspar is orthoclase, but plagioclase also occurs.

The **Intermediate** group is characterised by rocks containing little or no quartz and more plagioclase felspar than orthoclase.

In the **Basic** group the rocks usually contain no quartz and very little orthoclase, but olivine is very often present.

In the **Ultra-basic** group the rocks are largely composed of olivine combined with other ferromagnesian minerals and iron ores.

Chemical Constituents. The oxides of iron and magnesium are of considerable importance, especially in the basic rocks. The alkalies, potash and soda, are, however, the most important constituents of rocks, notably in felspars, micas, amphiboles, and pyroxenes. Phosphoric acid and titanic acid are present in most basic rocks in the shape of phosphate of lime (apatite), or titaniferous iron ore (ilmenite) and sphene (titanosilicate of lime). Fluorine, chlorine, and sulphur also occur.

Mineral Constituents. Plutonic and volcanic rocks are, speaking generally, composed of the same minerals, felspars, micas, hornblende, augite, and other common silicates being their principal components. Sometimes plutonic and volcanic rocks are even composed of the same minerals mixed in the same proportions.

Aqueous Rocks

Arenaceous Rocks. The commonest constituents of sands are minerals, such as white mica and quartz, which are least liable to chemical change, as the materials which formed the rocks from which the sands were derived have probably been subjected to chemical action during the processes of disintegration, transportation, and deposition.

Other constituents may be found locally, such as garnet, flint, tourmaline, or ilmenite. The *cement* may be calcareous, ferruginous, or siliceous.

In **Argillaceous Rocks** the constituents cannot easily be identified owing to their minuteness. The derived portions may be quartz,

felspars, or micas; carbonates, pyrites, and glauconite also occur. The *base*, which is of exceedingly fine texture, is probably often of micaceous origin, though formerly it was supposed to be kaolin.

Calcareous Rocks. These are composed, as a rule, of calcareous organisms, the hard parts of which consist chiefly of calcite or aragonite (see Chapter V, Section II). Impure calcareous rocks contain sand and fine detritus, etc. In dolomitic limestones and dolomites a portion or the whole of the calcite is replaced by dolomite.

Metamorphic Rocks

The principal change in composition is due to recrystallisation, and while the chief original minerals are not much altered, accessory minerals are developed during the process of alteration.

SECTION III. STRUCTURE

The terms 'structure' and 'texture' are often used indiscriminately, but it is preferable to limit the use of the latter term to the nature of the surface, as 'rough,' 'even-grained,' etc., while the former term is used to denote the method in which the component parts of a solid are built up.

General Terms. The various kinds of structure of rocks are described below according to their classification, as Igneous, Aqueous, or Metamorphic; but the following terms are used in a general sense :—

Crystalline, composed of angular grains or particles more or less crystallised in place, and not of rounded fragments of pre-existent masses. For 'Holocrystalline,' 'Hemicrystalline,' 'Microcrystalline,' see under *Igneous Rocks*.

Cryptocrystalline, composed of minute crystals invisible to the naked eye.

Granular, composed of approximately equal grains, either crystalline in outline or rounded by attrition.

Cellular or *Vesicular*, containing small spherical or bubble-shaped cavities. For 'Pumiceous,' 'Scoriaceous,' 'Amygdaloidal,' see under *Igneous Rocks*.

Lithoidal, a dull, very close-grained structure giving the rock a strong appearance, such as the 'lithoidal lavas' of old continental writers. They may or may not contain some glassy matter. The term lithoidal is used in opposition to vitreous, and is especially applied

to rocks formerly glassy which have become partially devitrified, *e.g.* obsidian.

Massive, without definite crystalline form.

Compact, so closely grained that no component particles or crystals can be recognised by the eye—a term used in field observation (see Chapter VI, Section III).

Brecciated, composed of breccia or rock consisting of angular fragments bedded in a matrix. The fragments may be composed of volcanic rocks or limestones, sandstones, siliceous cherts, etc., and the matrix usually consists of corresponding materials. Breccia is distinguished from conglomerates (see *Aqueous Rocks* below) by the sharpness and unworn condition of the fragments.

Breccias are formed in several ways :—

(*a*) By erosion and consolidation—atmospheric agencies detaching pieces of rock which become consolidated into masses of rock by pressure and induration.

(*b*) Volcanic breccias are formed as described in Chapter I, Section II.

(*c*) Volcanic fluxion-breccias are due to brittle lavas being broken up by pressure.

(*d*) Crush breccias and friction breccias are formed in fissures, veins, and faults.

Geode. A nodule or concretion-like mass of stone having a cavity lined with mineral matter or crystals pointing inwards. Common in all kinds of rocks, and in mineral veins.

Igneous Rocks

The same uprising molten magma, according to the situation in which it cools and consolidates, may form (*cf.* Chapter II, Section I) (*a*) an effusive stream or lava that issued from a vein or fissure, or (*b*) an intrusive boss, vein, dyke, or sill.

A molten magma is naturally in a slaggy or glassy condition. When it cools rapidly, its glassy structure is retained, but when it cools slowly a crystalline structure is developed. Between the vitreous and crystalline structures there will be a great number of intermediate forms which vary according to the rate and conditions under which the magma is cooled.

Devitrification is merely a process of crystallisation, and when the glass has been entirely replaced with crystals, the rock is completely devitrified.

Crystallites or *Microlites* are tiny rods and plates which are the

first form of crystalline structure to appear as the glassy magma cools. When the magma cools slowly, they build up crystal forms, but when it cools more rapidly they are unable to do so.

Ground-mass. Many igneous rocks consist partly or entirely of a paste or matrix, the nature of which cannot be determined without a microscope. This paste is termed the *ground-mass*.

Varieties of Structure. The following varieties are arranged in alphabetical order. The letters affixed to the names of structures denote the description of rocks to which each variety of structure is most generally applicable, as follows :—

H. Holocrystalline Rocks.
L. Lithoidal Rocks.
V. Vitreous or Glassy Rocks.
V.F. Volcanic Fragmental Rocks.

The *granitic* and *porphyritic* structures are the two principal ones among plutonic rocks.

Agglomerate (V.F.) consists typically of irregular, angular, subangular, or partly rounded blocks of various igneous rocks, usually of volcanic origin, often mixed with more or less material of rudimentary origin, and embedded in a matrix, similar in nature to the coarser fragments, but usually fine-grained.

Agglomerates are coarser and less often well-bedded than ordinary ash beds or tuffs. The blocks are often very large, and pieces of limestone, sandstone, or shale may occur mixed with volcanic materials, and be altered and recrystallised by contact with the heated igneous rocks and gasses. They are often found in volcanic ' necks.'

Amygdaloidal (V.). See ' Pumiceous.'

Aphanitic (H.) (see *Aphanite*, General Terms, Chapter V, Section I). A term still used to denote a compact, crystalline, and fine-grained rock the exact classification of which is unknown.

Banded or *Ribboned* (H.L.V.). Owing to the slow motion of the rock while cooling, layers of crystals or glassy aggregates lie in long strips or bands, one above another and more or less parallel, distinguishable by differences in colour and other properties.

Columnar (H.V.). The rock is divided into long prismatic columns, best seen in the basalt of the Giant's Causeway, also in felstones and granite.

Dendritic (H.). A term applied to the branch-like aggregation of dark metallic oxides, such as native copper, oxide of manganese,

Eye-structure. Large crystals developed during metamorphism, cause the smaller constituents to fold over and flow round them, tailing out on either side so as to resemble an eye; *cf.* 'Augen-gneiss,' etc.

Fibrous. Consisting of minerals with fibrous structure, *e.g.* actinolite schist, etc.

Fluidal, as described under 'Igneous Rocks,' is seen in vitrified sandstones.

Foliation. (See Chapter II, Section III.)

Mylonitic structure. Shear-breccia composed of flakes and particles of rock, which have been pulverised by dynamic metamorphism in mountain regions.

SECTION IV. PHYSICAL CHARACTERS

Hardness is a character of the immediate constituents or minerals of which rock is composed, and is only important as a rock-character when the rock is so fine in grain that the hardness of the individual constituent cannot be separately determined, or when the adhesion of the different constituents to each other is of appreciable importance as compared with the cohesion of the parts of a constituent.

For *determination* of hardness, see Chapter VI, Section III. The scale of hardness is given in Chapter III, Section I.

Fracture. The character of the surface of fracture of a rock depends on the kind of fracture of each of the constituents, on the sizes and arrangement of the constituents, on their modes of union, and on their cohesive and adhesive power. The terms used are the same as in the case of minerals (see Chapter III, Section I), and the following are typical examples :—

Conchoidal .	Flint.	Uneven .	Basalt.
Even . .	Chert.	Splintery .	Cast iron.

Colour and Lustre. Owing to the varieties of colour and lustre met with in one and the same rock, they are comparatively unimportant, but some indication of the nature of a rock may be obtained from them if due caution is observed.

Iron is one of the most important colouring agents. Scarcely any rock is free from iron. In many it is present as ferrous carbonate, which is *white* when pure and therefore imparts no colour to the rock. Rocks which contain iron under this form are usually *bluish* or *greyish*, the colour being due sometimes to organic matter,

sometimes to various inorganic substances. Rocks, however, seldom show this bluish or greyish hue except at some depth below the surface, or where they have been otherwise shielded from the action of the air. Where they have been exposed they are commonly *red, brown,* or *yellow.*

Ferrous carbonate is an unstable compound, and under the oxidising influence of the atmosphere and of water becomes converted either into ferric oxide ($2FeCO_3 + O = Fe_2O_3 + 2CO_2$) or one of the ferric hydrates, and the colours given by these compounds are strong enough to overpower the original grey hue of the rock. Ferric oxide colours red; ferric hydrate generally produces some tint of brown or yellow, the exact shade depending perhaps on the degree of hydration.

The student may observe instances of this change of colour in the sinking of shafts or wells: the sandstones brought up from any depth are almost invariably blue or grey; the same beds when quarried at the surface are brown or yellow. The same difference may be noticed between the top and bottom beds of a deep quarry. It is not uncommon, too, to come across blocks of stone which are blue inside, 'blue-hearted,' and have a brown or yellow outside crust. This change has naturally gone on to a larger extent in porous rocks, like sandstone, than in impervious clayey rocks.

The *blue* colour of rocks is caused by finely disseminated iron pyrites in some cases, in others perhaps by ferrosoferric phosphate; the latter salt may also be the cause of the *green* colour of certain rocks, while in other cases this colour may be due to a silicate of iron, and sometimes perhaps to a ferric hydrate or a ferrosoferric hydrate.

A *white* colour may be due to the absence of metallic oxides, or to weathering or bleaching (see Chapter V, Section IV.

Organic matter will colour clays and other rocks from *light grey* to *black*; and in some sandstones black patches of colour are due to the presence of peroxide of manganese. Carbonaceous matter, of course, usually gives a black colour, and so at times does iron in the form of ilmenite or magnetite.

Lustre. The terms used for minerals (see Chapter III, Section I), apply equally to rocks, but this quality is not of the same value in the latter case.

Streak. While the hardness is being tried, the colour and lustre of the streak or mark left on paper by the abraded powder

(*cf.* Chapter III, Section I, in the case of minerals) should also be observed.

Feel and Smell are distinctive in the case of certain rocks; *e.g.* talcose and other magnesian rocks often have a soapy or greasy feel, and trachyte is notably rough. Some rocks have a distinct bituminous odour.

Magnetism is important in the cases of rocks containing magnetite, etc.

CHAPTER V

ROCKS

In this chapter an attempt has been made to describe the more important rocks in such a way that the engineer may be able to distinguish them with comparative ease. The science of petrology has, however, advanced considerably of late years and the various types have been found to grade into one another, so that, especially among igneous rocks, the nomenclature is almost bewildering, and differs, moreover, in the various text-books. For more detailed descriptions, therefore, especially as regards microscopic characters, reference should be made to text-books on petrology.

The engineer who desires to identify specimens of rocks will do well to compare them with those to be found in any good geological or mineralogical museum, and with the aid of the following descriptions he should be enabled to identify any ordinary rock.

SECTION I. IGNEOUS ROCKS

General Terms

Felsite. A term formerly and still to some extent used to denote fine-grained igneous rocks of acid or subacid composition. They are generally so fine-grained that their ingredients are not distinguishable by the naked eye. They consist for the most part of minute particles of felspar and quartz. Those containing porphyritic crystals of quartz are known as quartz-felsites (see Hypabyssal Rocks: Quartz-porphyry). Soda-felsites contain an abundance of soda-felspar.

The felsites are now generally separated into granite-porphyries, orthoclase-porphyries, felsitic-rhyolites, granophyres, micro-granites, etc.

The term *felsite* or *microfelsite* or *felsitic matter* is still used to denote the very fine ground-mass of rhyolites, dacites, and porphyries.

Trap Rocks. The basalts and felstones or claystones, as well as the rocks known as greenstones or whinstones, are often all included under the name of trap-rocks, but the term trap is more properly

applied to the dark compact greenstones or basalts of which the successive streams have flowed in great horizontal sheets and have given rise to a step-like structure, as in the case of the lavas of the Faroe Islands, the Deccan, Norway, etc.

Aphanite. A name formerly given to fine-grained dark igneous rocks the ingredients of which are not distinguishable by the naked eye. They consist essentially of plagioclase felspar with augite or hornblende, and possibly some quartz or biotite. Those with hornblende are now classed as diorites, etc., and those with augite as dolerites, etc.

Plutonic[1] Rocks

Acid Group

Granites. Occur in large masses or bosses with veins and dykes (see Chapter II, Section I). (See Chapter VIII for further details.) It has also remarkable weathering properties. Specific gravity about 2·65. The typical granitic structure is holocrystalline, with no paste or matrix, the crystals or grains all touching one another. They are usually compact, but sometimes porous, and the crystals vary in size from a mustard seed to that of a closed fist. Varieties of granite due to structural differences are porphyritic granite, gneissose granite, graphic granite, pegmatite, and eurite (see below).

Granites are aggregates of quartz and felspar with mica, hornblende, or augite as accessories. Varieties due to differences in composition are described below.

The *quartz* usually occurs in more or less angular grains, but not often with the crystalline faces perfectly developed. It is recognisable by its vitreous lustre, conchoidal fracture, and absence of cleavage, and is either colourless or has a smoky tinge.

The *felspar* is usually orthoclase, but plagioclase (oligoclase or albite) occurs; orthoclase is generally the predominating mineral. It usually occurs in twin crystals, cleaves with a pearly fracture, and gives granite its characteristic colour, being pink, red or brownish red, white, yellowish grey, green or reddish grey, and even blue in Connecticut and the Pyrenees. The oligoclase is less transparent, contains more soda than orthoclase, is more fusible, and has a grey or greenish tinge. Albite and labradorite also occur.

The *mica* generally occurs in thin plates which are often hexagonal. Crystals are rare. It varies in colour, being silvery white, brown, or black. The white potash mica (muscovite) is rarer and

[1] Or Abyssal.

more diffused than the black magnesian mica (biotite). Both kinds often occur together. The dull edges of biotite crystals often resemble fibrous hornblende, but the lustre of the basal planes will easily serve to identify them. Certain large-grained granites contain lithia mica.

The *hornblende* crystals are irregular. They show a prismatic cleavage and are green or brownish green.

Granite proper contains both light and dark micas, and the quartz and felspar are in approximately equal proportions.

Muscovite granite has white mica only.

Biotite granite or *granitite* has only dark mica, oligoclase predominates, and quartz is of reduced importance.

Hornblende granite or *syenitic granite* is intermediate between typical granite and syenite. It contains less quartz than granite, and hornblende to a large extent replaces the mica, which is always dark.

Augite granite is of rare occurrence.

Protogenic or *talc granite* of the Alps has the same composition as granite, but contains in addition a pale green, talc-like mineral. Its quartz is easily broken. The oligoclase has a greenish tinge, while the orthoclase is grey. The mica is usually in six-sided plates. The talc is only freely developed when the rock becomes schistose.

Gneissose granite is granite which has a schistose character.

Graphic granite is also schistose, but consists of orthoclase and quartz so arranged in parallel layers that a transverse fracture exhibits the quartz in forms suggesting letters of an Oriental language. It occurs near Ilmenau, and by Limoges, etc.

Pegmatite is a kind of giant granite in which the crystals of orthoclase are sometimes a foot long, and the white mica occurs in large flakes.

It usually occurs in dyke-like masses, sheets, or veins, not generally in the form of large irregular bosses like the commoner massive fine-grained granite. The pegmatites, which contain muscovite in large crystals, are exclusively acid (siliceous) in composition, having in general the mineral composition of granite.

It is seen near Penig in Saxony. Sometimes the greater part of the rock is formed in a milk-white quartz. It occurs in Ireland, and is frequently cavernous, with the walls of the cavities covered with crystals.

Porphyritic granite contains large porphyritic crystals of ortho-

clase. The ground-mass is composed of the same constituents as ordinary granite.

Micropegmatite or *granophyre* shows the same texture on a minute scale as pegmatite does on a large scale, and is often so exceedingly fine-grained that its component parts—quartz and alkali felspar—cannot be detected by the microscope.

Tourmaline granite is granite in which the mica is partly replaced by schorl. The felspar is flesh-coloured, and there is very little quartz. *Luxulyanite* is a tourmaline granite obtained near the village of Luxullian in Cornwall.

Granulite is a name given by French geologists to a granite containing both muscovite and biotite, but German geologists use this name for a metamorphic rock (see Section III), and English and American geologists generally follow this practice.

Schorl rock is a crystalline aggregate of quartz and tourmaline, usually granular and massive, and grey or dark coloured when there is much schorl present. It is hard, splintery, and resists weathering. Schorl rocks almost always occur in association with tourmaline granites, and usually originate from pneumatolytic action on granites, porphyries, etc.

Greisen is a modification of granite the essential constituents of which are muscovite and quartz. It is distinguished from granite by the absence of felspar and biotite; common accessory minerals are apatite, tourmaline, topaz, fluor-spar, and iron oxides. It resembles granite in colour though often somewhat paler ; hard specimens have a glistening appearance due to the crystals of white mica. It occurs in belts or veins intersecting granite, and is probably due to the alteration of granite. It resembles schorl rock both in mode of origin and mineralogical composition.

Eurite, *Aplite*, *Micro-granite*, *Elvan* and *Quartz-felsite* (see Quartz-porphyry under 'Hypabyssal Rocks' below).

Felsite (see Rhyolite under 'Volcanic Rocks' below).

Intermediate Group

Syenites are holocrystalline in structure like granites, and the texture is even grained. They occur in bosses and dykes but are much less common than granite. They consist essentially of orthoclase felspar with one of the ferromagnesian group ;[1] according

[1] A group embracing minerals formed by the union of silica with iron, magnesia and lime together with some other basic oxides, and includes pyroxenes, amphiboles, biotite and olivine.

to the nature of the latter we have *hornblende-syenite* or syenite proper, *augite-syenite* and *mica-syenite*. The important difference from granite is the absence or scarcity of quartz.

The orthoclase is usually white or pink and forms about half of the rock. The hornblende is usually green, but is sometimes brown or dark blue. It commonly occurs in lamellar and columnar crystals, and encloses magnetite, apatite, brown mica, and titanite. The augite is usually colourless or very pale green. The mica is nearly always brown. Accessory minerals are plagioclase, sphene, apatite, zircon, magnetite, and pyrites.

Hornblende-syenite is the typical syenite, and occurs in Germany, Piedmont, etc., usually with hornblende granites and diorites.

Augite-syenite is found in Saxony and Norway. In the latter country the most abundant type is *laurvikite*, which has an iridescent appearance. A similar rock occurs in Texas.

Mica-syenites are not common. Most of the rocks formerly known as mica-syenites are now called *minettes*. See 'Lamprophyre' (Basic Group of Hypabyssal Rocks).

Nordmarkite is a quartz-syenite—a transitional form between granite and syenite, and occurs in Norway, Sweden, and Scotland.

Monzonite is a dark grey rock, differing from granite and syenite in containing nearly equal parts of plagioclase and orthoclase felspar. It has much augite and large brown plates of bronzite.

Nepheline-syenite. The nepheline in the coarse elæolite form resembles brownish or greenish quartz, but may be distinguished by the knife and by its characteristic greasy lustre. The varieties with hornblende have been called *foyaite*, from Foya in Algarve, and those with mica *miascite*, from Miask in the Urals.

Diorite. Occurs generally as dykes. Specific gravity, 2·85 to 3·0. Like syenite it has a holocrystalline granitoid structure, while ophitic structure is found in the more basic varieties. The texture varies from fine to fairly coarse. Differs from syenite in having a soda-lime felspar instead of orthoclase as one of its principal constituents. The other principal constituent is usually green hornblende, but mica, augite, and enstatite also occur. Quartz may be present, and when in considerable quantity the rock is termed *Quartz-diorite*.

Tonalite is a quartz-diorite containing biotite and hornblende

in nearly equal proportions, resembling but usually darker than granite.

Napoleonite or *Corsite* is a variety of diorite, characterised by orbicular structure.

Basic Group

Gabbro. Occurs as dykes or in large boss-like intrusions. A granitoid rock, used to some extent for building under the commercial name of granite. Belongs to both the Intermediate and the Basic Groups. Specific gravity, 2·9 to 3·02. Holocrystalline and granitic in structure, the texture varying from medium to coarse grain. Consists essentially of a lime-soda felspar, usually labradorite, but sometimes anorthite, and a pyroxene, usually diallage, which often fills up the spaces between the felspar, its cleavage surfaces having a marked metallic or pearly lustre.

In *gabbro proper*, diallage or augite predominates; *hornblende gabbro* contains hornblende in addition which is green or brown; *olivine gabbro*, in addition to hornblende and augite, contains olivine which, when fresh, is colourless, but is often stained with limonite; in *norite*, diallage is replaced by hypersthene, which has a coppery lustre.

The name gabbro is sometimes restricted to varieties containing olivine, which are more basic; while the intermediate types, in which no olivine is present, are known as *pyroxene diorites*.

Pyroxenites consist of minerals of the pyroxene group, and are sometimes known according to the predominant mineral as pyroxenite (augite), diallagite, hypersthenite, bronzitite, and websterite (diallage and hypersthene). Hornblendites are allied, and the whole group is known as *perknite*. They are closely allied to the gabbros and norites, but differ in having no felspar, and to the peridotites, which differ in containing olivine. They are usually very coarse-grained and pass into serpentine by decomposition.

Ultra-Basic Group

Peridotites. Specific gravity, 3·0 and over. Holocrystalline in structure, sometimes granular or porphyritic. Composed very largely of olivine and nearly always devoid of felspar; contain much iron and magnesia; weather easily and frequently change to serpentine. They are very often poikilitic, small rounded olivine crystals being embedded in masses of pyroxene or hornblende.

Hypabyssal Rocks

The igneous rocks included under this head usually occur in the form of dykes, and probably are protruded from deep-seated bosses. Most are holocrystalline, but in some there is a glassy residue. They are usually compact, but some have a vesicular and others a porphyritic structure.

Acid Group

Granite-porphyry. A fine-grained granitoid rock with a holocrystalline or micropegmatitic matrix, with large phenocrysts of orthoclase and plagioclase, and smaller fragments of quartz, biotite, and occasionally hornblende or pyroxene. It is generally found associated with granite.

Quartz-porphyries. Also known as *felsites*, *quartz-felsites*, or *elvans*. Specific gravity about 2·65. Colour varying from white to dirty yellow. Frequently occur as dykes and veins near granite bosses.

The ground-mass is compact or more or less crystalline, consisting of quartz and felspar, with embedded crystals of quartz and orthoclase, and sometimes biotite. Many of the fine-grained varieties cannot be differentiated from *micro-granite.*

If consisting only of quartz and orthoclase in a felsitic ground-mass, the rock is known as *aplite.*

Eurite is the French equivalent of 'felsite.'

Elvan is a Cornish name for quartz-porphyry, but the same term is used for china-stone.

Intermediate Group

Holocrystalline rocks with porphyritic structure and felspar phenocrysts. Divided into (a) *Porphyries*—orthoclase predominating and related to syenites; (b) *Porphyrites*—plagioclase predominating and related to diorites.

Porphyry. A general term denoting rocks which contain an alkali felspar, and occupy a position structurally between porphyritic granites and rhyolite.

Porphyries include the following varieties:—

Orthoclase-porphyry (felspar-porphyry) includes *syenite-porphyry* and *orthophyre*, though the latter term also includes some eurites. It contains little or no free quartz, and bears the same relation to syenite that granite-porphyry does to granite, and includes many so-called *felstones*. The ground-mass is principally alkali felspar

with sometimes a little quartz; the phenocrysts are orthoclase (or oligoclase), with biotite, hornblende, or augite.

Elæolite-porphyry contains porphyritic nepheline, often weathered to soft, finely crystalline aggregates of white mica.

Porphyrites have a porphyritic texture with phenocrysts of plagioclase felspar and hornblende, biotite or augite, in a fine-grained mass. The name porphyrite was formerly given to altered andesites, etc. They often occur as dykes accompanying masses of diorite, and are then called *diorite-porphyrites*. *Hornblende-porphyrite* contains plagioclase hornblende and biotite; *mica-porphyrite* contains plagioclase and biotite. *Norite-porphyrites* have porphyritic plagioclase with hypersthene or bronzite and accompanying norite masses.

Basic Group

Lamprophyres. A family of fine-grained, dark-coloured, usually much altered dyke rocks, rich in hornblende, augite, or biotite. They include *minette*, *kersanite*, and *mica-trap*.

Dolerites occur in dykes and sills and lava flows. They are generally holocrystalline and coarse-grained, and their essential minerals and chemical composition are similar to basalts (see 'Volcanic Rocks'). Many dolerites are porphyritic. They consist of plagioclase felspar and augite, with olivine, hornblende, mica, or enstatite.

Quartz-dolerite contains a small amount of quartz and is often micropegmatitic.

Diabase is a name given to a doleritic rock in which a greenish chloritic colour has been imparted by the alteration of the olivine or augite.

Variolites[1] are dark green basic igneous rocks which have become much decomposed, and whose weathered surfaces show pale coloured spots or markings like pock marks. They are akin to basalts and diabases, and also occur as an alternative form of dolerites.

VOLCANIC ROCKS

Acid Group

Rhyolite. The volcanic equivalent of granite, and corresponds with quartz-porphyry. It is also called *quartz-trachyte* and *liparite*. Specific gravity about 2·5. It is compact, lithoidal, or porphyritic, often with marked fluidal, perlitic, and spherulitic

[1] Variola = Smallpox.

structure, and has a glassy ground-mass. Highly acidic. Consists of quartz and orthoclase with either mica, hornblende, or pyroxene in a light-coloured ground-mass, like that found in trachyte, chiefly composed of microliths of felspar.

Nevadite is a crystalline and granitoid variety of rhyolite.

Obsidian is a term which includes both rhyolite glass and trachyte glass. These glasses have a low specific gravity, a marked conchoidal fracture, and a high fusibility.

Felsite. This term was formerly used to describe many rocks which are now known as rhyolites, but its use is now restricted to the felsitic structure described under 'General Terms' in this Section.

Pitchstone is almost identical with obsidian, but is less glassy and has a greasy or pitch-like lustre, and a fracture more or less conchoidal and at times rather splintery. It contains more water than obsidian, and is generally dark green or brown in colour, but sometimes dark yellow or red.

Intermediate Group

Trachyte. The volcanic equivalent of syenite, and corresponds with felspar-porphyry. Specific gravity about 2·5. Compact and lithoidal in structure and very often scoriaceous, causing the rough texture from which the name is derived. Usually pale in colour, but reddish, yellowish, or even black trachytes are found. Constituents are the same as those of syenite, the orthoclase being usually sanidine in large, plate-like crystals which are porphyritic, the ground-mass being felsitic.

Phonolite or *Nepheline-trachyte* is the volcanic equivalent of nepheline-syenite, and is commonly known as *clinkstone*, as it emits a ringing sound when struck. Specific gravity about 2·55. Compact, lithoidal, or glassy in structure, of greyish-green colour and spotted appearance. Sometimes has a fissile character, and splits into slabs which can be used for roofing. The fissile character is intensified by weathering, which also includes a spheroidal or onion-like structure in the decomposing rock.

It consists of sanidine and nepheline with a ferromagnesian constituent; sometimes leucite is present in combination with or replacing nepheline.

Bostonite. A fine-grained, light-coloured grey or pinkish rock consisting essentially of alkali felspar; is very similar in composition to trachyte, and often occurs with nepheline-syenite.

Andesites. Dark-coloured lavas prevalent in the Andes; the volcanic equivalent of diorite. They consist chiefly of a glassy, plagioclase felspar, with mica, hornblende, or pyroxene, and a lithoidal to glassy ground-mass. The absence of orthoclase is characteristic. They vary in colour from grey to dark green, and when hornblende abounds may be dark brown or black. They occupy an intermediate position between trachyte and basalt.

Trachytic andesite (mica or hornblende andesite) has a structure like that of trachyte, and is commonly porphyritic. The ground-mass is characteristically trachytic, and the colour is usually darker than that of trachyte. Specific gravity about 2·75.

Basaltic andesites (pyroxene andesites). Structure lithoidal, sometimes with glassy interspaces between the crystals. They are darker than the trachytic andesites, and approach basalts in texture, becoming even black and notably heavy. The fracture is conchoidal. Specific gravity, 2·75 to 2·9.

Quartz-andesite or *Dacite* contains a considerable proportion of quartz, but otherwise resembles the trachytic andesites, though it has some features in common with rhyolites. Specific gravity about 2·65.

Altered andesites, in which the glassy matrix is replaced by a brown earthy base, are sometimes called *porphyrites*, but this term is now used for rocks resembling porphyry, but having a soda-lime felspar; they are the plutonic equivalents of andesite. Those altered by thermal waters, steam, or gases are sometimes called *propylites*.

Basalts occur as lavas, sills, and dykes. They are very compact, black, dark brown, or greenish rocks varying in structure from holocrystalline to semi-vitreous, and sometimes porphyritic or ophitic. They often form immense dykes, with a tendency to cleave into hexagonal columns as on the Giant's Causeway. They consist of plagioclase and augite, with olivine in the most basic varieties, and magnetite, ilmenite, and apatite. Specific gravity, 2·9. They are the volcanic equivalents of gabbro.

When olivine or hornblende occurs, the rock is known as *olivine-basalt* or *hornblende-basalt*; if nepheline or lencite entirely replaces the felspar, the rock is called *nepheline-basalt* or *leucite-basalt*.

Tachylyte is a basaltic obsidian, black, often vesicular or spherulitic, weathering to dark brown or red, and when much decomposed is known as *palagonite*.

In those basalts in which the phenocrysts are embedded in

a holocrystalline ground-mass we get rocks that are essentially dolerites.

Anamesite, diabase-porphyrite, and *melaphyre* are names given to the older rocks to indicate more or less altered basalts and dolerites.

Basaltic lavas are often spongy or pumiceous, the cavities being filled with calcite, chlorite, and zeolites.

Nephelinites are lavas with nepheline and augite. Lavas with nepheline, augite, and olivine are called *nepheline-basalts* ; those with plagioclase in addition are called *nepheline-basanites.* Lavas with nepheline, plagioclase, and augite are *nepheline-tephrites.*

Volcanic Fragmental Rocks (*Pyroclastic*)

As these rocks are bedded, they are often included with other bedded rocks under the general term 'Sedimentary Rocks,' but it seems preferable to class them, according to their mode of origin, among the igneous rocks.

As regards *volcanic ejecta* (see Chapter I, Section II), *volcanic sands* are mere water-worn deposits the materials of which have been derived from some neighbouring volcanic area.

Volcanic Agglomerates or **Coarse Tuffs.** As described in Chapter I, Section II, these are derived from volcanic ashes, etc., which have consolidated. The older tuffs are generally very compact and solid, while the younger are light porous rocks. Volcanic bombs and lapilli are frequently embedded in the ashes and dust, and may be angular or spheroidal or twisted and ropy, with a rusty brown colour. They often are scoriaceous and amygdaloidal. The whole forms a conglomerate and often has joint planes traversing it.

Tuffs and **Ashes.** The fine ashes form compact masses, but the tuffs mixed with them may contain embedded crystals of augite or felspar and lava blocks. Weathering shows a coarsely fragmental structure.

Trass. A local name for a volcanic tuff found in the Eifel. It is a fragmental rock, grey or cream-coloured, and chiefly composed of pumiceous dust. It may be considered a trachytic tuff, and is chiefly used to impart hydraulicity to lime, but in a compact form is used for building purposes and as a fire-stone.

Pozzolana or **Pozzuolana.** A decomposed tuff, of basic character, which looks like red sandy earth, and lies in extensive beds under and round the city of Rome. It is used like trass to form hydraulic cement (see Chapter X).

SECTION II. AQUEOUS ROCKS

These consist of the stratified rocks which have been formed by deposition in water. The pyroclastic, sedimentary rocks which have been formed from volcanic fragments have been already described in Section I.

Aqueous rocks may be divided into (1) detrital (fragmental or clastic) rocks, viz. formed from materials derived from older rocks; (2) rocks formed by chemical or organic agencies.

Detrital (Fragmental or Clastic) Rocks

These consist of pebbles, sand, or mud which have become hardened by various natural cements into solid beds or strata. The pebbles then become a conglomerate, the sand a sandstone, and the mud a mudstone clay or shale. *Mud* is the fine, almost impalpable material produced by erosion and formed by natural agencies into a stiff paste with water. According to the rocks from which it is derived, it may consist of limestone, sand, or clay, or mixtures of these and other materials in any proportion. It often contains a considerable amount of vegetable matter. *Mudstone* is an earthy rock with no definite structure, and apparently composed of compressed dried mud. It bears a relation to mud similar to that of sandstone to sand.

Detrital rocks are all mechanical deposits, and vary indefinitely in composition according to the nature of the sources from which they were derived. They may be divided into (i) *arenaceous* or sandy rocks, and (ii) *argillaceous* or clayey rocks.

(i) *Arenaceous Rocks*

Sand. 'By this term we understand the materials constituting the fine-grained siliceous rocks called sandstone. This sand has in every case been derived from the destruction of igneous or metamorphic rocks, and in some cases of cherts or flints. Quartz is by far the commonest ingredient of sands. The quartz from granite consists of separate grains which often have an irregular and complex form, but the quartz from felsite is much more truly crystalline, and the planes of the crystals are frequently perfect, though the angles are more rounded than in the quartz from granite. Sometimes the grains are corroded as though partly dissolved by the action of the alkalies liberated when the associated felspar was decomposed. The quartz derived from gneiss and mica-schist,

especially when those rocks have a thin foliation, is remarkable for being flattened in the plane of foliation, and consists of numerous small crystals dovetailed together, so that when broken up it gives rise to a fine-grained sand, or a sand containing grains which show a compound structure; and if the parent rock contained *mica*, thin plates of mica are found between the parallel grains of quartz.'[1]

The *felspar* which is usually associated with quartz is generally quickly decomposed, but a small amount often remains in the sand. In addition to the above, sands generally contain other ordinary rock-forming minerals, *e.g.* garnet, tourmaline, zircon, anatase, and rutile which resist decomposition; less common ingredients are hornblende, augite, chlorite, iron oxides, andalusite, etc.

'The grains of sand are rarely obtained direct from the rock which yields them without experiencing a large amount of wear. This attrition is due to transport of the material by rivers, and grinding by the waves on the seashore. Some ancient sand-beds are made up of grains which are unworn and practically new, while the grains on many a modern sea-beach are of vast antiquity, and have formed part of several geological formations, in each of which they have been worn. When we examine some of the modern sands in process of formation, the amount of wear is found to be unexpectedly small; thus the sand of the river-terraces at Dunkeld is almost entirely angular, and presents the features characteristic of sand derived from schists. The sands of the Arabian, Egyptian, and great African deserts, on the other hand, are exceptionally worn, every grain presenting the characters of a miniature pebble, a feature resulting from the agency of wind in rubbing the grains against each other.'[1]

Sandstone consists of grains of sand compacted by some cementing medium, which may be calcareous, ferruginous, siliceous, or a mixture of some of these. The *calcareous* cement has probably been originally deposited in the form of mud, etc., at the same time as the sand grains, but has had no binding effect until it has been dissolved and redeposited with a more or less crystalline texture. *Ferruginous* cement may occur alone or associated with calcareous matter. The red oxide of iron and brown hydrated oxide both occur and often form a thin coat round each grain. When the cement is *siliceous* it is often deposited in crystalline continuity with the quartz grains. *Argillaceous* cement also occurs formed by the decomposition of felspars, etc.

[1] Phillips: *Manual of Geology*, Part I, H. G. Seeley, pp. 92–93.

When sandstone is capable of being easily dressed by the hammer for building purposes it is denominated *freestone*, and when capable of being split up into large sheets for paving, etc., it is known as *flagstone*.

Gannister. (See Chapter IX, ' Refractory Materials.')

Grit is a hard and firm sandstone formed of coarse, sharp grains.

Sandstones are described as *micaceous*, *felspathic*, *quartzose*, *glauconitic*, according to the nature of their materials.

Bluestone is a bluish, fine-grained, argillaceous sandstone used for flagging and building. The term is also used locally for any stone of a blue-grey colour.

Buhrstone is a cellular variety of chalcedonic silica. Occurs in the Paris tertiary basin and is much used for millstones (*cf.* eocene of Alabama. Synonymous for cowstones or doggers).

Quarzite (see also under Altered Rocks, Section III). When a deposit of quartz-sand has become completely compacted by a cement of quartz, the result is a quartzite, but one in which the original grains and cementing material are clearly distinguishable.

Conglomerate (Puddingstone). A coarsely fragmental rock composed of pebbles or fragments of pre-existing rocks set in a finer-grained matrix. The pebbles must be water-worn or rounded, for if angular the rock is known as a breccia. The pebbles consist chiefly of hard rocks such as granite, gneiss, quartzite, chert, flint, greywacke, sandstone, or limestone, and andesite, diorite, porphyry, and porphyrite occur. They vary in size from 10 to 20 feet in diameter to 1 foot or less. The matrix usually resembles the pebbles in composition, but also contains a considerable proportion of softer ingredients such as clay, felspar, mica, dolomite, and calcite.

Conglomerates are really consolidated gravels, and were generally formed on seashores or in shallow waters.

Greywacke is an old somewhat vague term used for sandstones belonging to the older geological periods, which are usually grey or brown and very impure. It is now used for greenish-grey felspathic sandstone.

The name **Arkose** is given to (*a*) a felspathic sandstone which may have been formed close to a mass of granite or similar rock, and thus contains all the minerals of the rock fitted close together by pressure ; and (*b*) a fragmental rock, usually yellowish brown, composed of crystals of disintegrated granite, which is also known as growanstone.

(ii) *Argillaceous Rocks*

Clay is fully described in Chapter IX. *Kaolin* or *Kaolinite*, which is a hydrous silicate of alumina, is a secondary mineral derived chiefly from the decomposition of felspars, and is commonly found in the form of *china clay*. It is often considered to be the basis of all clays, but even in purified clays, while there is a proportion of kaolinite crystals, there is a larger proportion of amorphous material known as *kaolinitic matter*, *clayite*, or *true clay*, whose chemical composition is the same as kaolinite.

Ordinary clays contain a certain amount of felspathic mud, and it is not easy to draw the line between clays and *mudstones*—the latter being composed essentially of felspathic mud with mixtures of other substances. For the practical purposes of the engineer the test of a clay is its plasticity and sectility.

Clays may contain, in addition to kaolin and felspar, some augite and hornblende and small particles of other minerals, *e.g.* quartz, calcite, pyrites, etc.

The size of the quartz grains in clay will give some idea of its origin: if derived from granite, they will be coarse; if from schists, they will be finer.

Marl is a mixture of clay and lime. *Marl slate* is calcareous shale.

Loam is a mixture of clay and sand.

Shale is indurated clay, mud, or silt which is more or less laminated. It is also known as *bind*, *blue bind*, *plate*, or *shiver*.

Arenaceous shale, *rock bind* or *stone bind*, is a sandy shale. *Carbonaceous shale*, *bass* or *batt*, contains enough carbonaceous matter to be easily distinguishable.

Oil shale contains bituminous matter. Shales containing iron pyrites are used for making alum, and are known as *alum shales*.

Rocks formed by Chemical or Organic Agencies

These may be divided into calcareous, siliceous, phosphatic, carbonaceous, and ferruginous.

(i) *Calcareous Rocks*

Limestone. Limestone may be formed from the waste of older limestones, from remains of mollusca and other organisms, or by chemical precipitation and deposition. It consists of pure carbonate of lime, or of carbonate of lime mixed with silica, alumina, iron,

etc. When any of these occurs in excess the rock is known as a *siliceous, argillaceous, arenaceous,* or *carbonaceous*, etc. limestone.

'The carbonate of lime sometimes exists in the crystalline form of calcite, sometimes in the form of aragonite, and many shells have one layer of calcite and the other layer of aragonite. There is no means known by which calcite can be changed into aragonite, the former being a remarkably stable substance, but aragonite is as strikingly unstable. When its temperature is raised it passes into a mass of crystals of calcite; it is also easily dissolved, and since calcite is usually deposited from cold solutions of carbonate of lime, it happens that organisms formed of aragonite are often removed entirely from a deposit, or replaced by structureless calcite. This difference explains not only the circumstance of preservation of many groups of fossils, but also important points in the general structure of limestones.' [1]

Physical characters. The colours are very varied; hardness about 3; specific gravity rather less than calcite—some compact varieties 2·6, those with aragonite 2·85. All effervesce with cold acid.

Vertical joints are common, and with the planes of bedding form the blocks and terraced cliffs so well known. The planes of lamination are not easily separable. Compact limestones show a clean fracture.

Concretions of silica in the form of *flint* and *chert* (see (ii) Siliceous Rocks) are common, and beds are often replaced by pseudomorphic action. *Stalactites* and *Travertine* are often found with limestones, chalk, etc.

Chalk is a white, fine-grained limestone containing at times as much as 94 to 98 per cent. of carbonate of lime. It may be quite soft and earthy, or harder and more compact, and frequently contains nodules of flint and iron pyrites.

Chalk marl is chalk mixed with clay.

Oolite or *Oolitic limestone* is usually a dull yellow colour, but grey oolite is found. Its peculiar structure makes it a 'freestone,' or one which can be cut in any given direction. Bath stone, Portland stone, etc., are oolitic limestones.

Pisolitic limestone is sometimes known as 'pea grit.'

Crystalline limestone has a coarse or fine crystalline structure, which may be due to alteration (see Section III) or to original structure, each crystal being a fragment of a fossil.

Brecciated limestone is fairly common where earth movements

[1] Phillips: *Manual of Geology*, Part I, H. G. Seeley, p. 106.

have taken place, cracks formed thereby becoming filled with calcite. It may consist largely of fossils which become deformed or of mineral fragments, and when associated with mica may be changed into 'calc-schist' (see Section III).

Stalactites and *Stalagmites* (see Chapter I, Section I) frequently show a crystalline structure, and fractured surfaces show successive layers which disclose the mode of deposition.

Travertine, which consists of carbonate of lime deposited on vegetable matter in streams, etc., often shows relics of such matter. It is generally pale or slightly tinged with brown or orange.

Rottenstone is a name given to the siliceous skeleton formed from siliceous limestone by the weathering out or decomposition of the calcareous part of the rock.

Cornstone is an arenaceous limestone in which the carbonate of lime is sufficiently predominant to enable it to be burnt for lime when better stone is not available. Arenaceous limestones pass into calcareous sandstones.

Carbonaceous or *Bituminous limestone* obtains its dark colour from the decomposition of vegetable or animal matter, and *fetid limestone* owes its smell to the same cause.

Coral limestones. Scattered corals occur in many shelly limestones; but occasionally the branching or astræan types build up reef-like masses among ordinary sediments, enclosing the coral detritus accumulated on their flanks, together with many remains of the organisms of the external sea.

Dolomite (dolomitic limestone). This rock is generally due to the alteration of ordinary limestone, a portion of the carbonate of lime being replaced by carbonate of magnesia. It forms extensive beds of *magnesian limestone*, and also occurs as an alteration product of limestone and aragonite. It is liable to contain cavities and hollows. Specific gravity about 2·8.

Its colour is usually brown or yellow, but white, grey, and black varieties occur. Dolomite is sometimes earthy and friable, sometimes splits easily into thin slabs, and sometimes forms large concretions.

Rock-salt (see Chapter III, Section II) occurs in beds and masses sometimes from 60 to 90 feet thick. It is frequently mixed with argillaceous, ferruginous, or bituminous earths which give it various colours, but is sometimes perfectly pure and white. It is often associated with gypsum.

Gypsum is a mineral (*cf.* Chapter III, Section II), composed of

sulphate of lime, which occurs in regular beds and in irregular concretionary masses, and also in veins and strings in other rocks. Specific gravity, 2·32. Does not effervesce with acids. Colour generally white. When compact, it resembles pure crystalline limestone, but hardness of only 2 distinguishes it. The crystalline varieties are known as *selenite*; the cryptocrystalline and fine-grained varieties are called *gypsum*; the compact, very fine-grained, and mottled varieties are known as *alabaster*; while the fibrous varieties with a silky lustre are called *satin-spar*.

(ii) *Siliceous Rocks*

Flint and Chert. These terms can be used synonymously for the concretions and beds of chalcedonic and amorphous silica found so frequently in limestones and sandy rocks. *Flint*, however, is brittle and breaks with a very marked conchoidal fracture, while *chert* is tough and breaks with a splintery fracture.

Flint fractures with a generally uniform and often conchoidal surface, and fragments are semi-transparent. Its hardness of about 7 is distinctive, and it is not affected by acids.

Nodules of flint and bands of chert are found along lines of stratification, and occur along joint planes and faulting lines in tabular form.

(iii) *Phosphatic Rocks*

Phosphorite (phosphatite), or phosphate rock, is a massive radiated variety of the mineral apatite (phosphate of lime), which occurs in a compact or earthy form, or in irregular concretionary masses or nodules, and is probably of organic origin. It is usually associated with clays, but occurs among both sandstones and limestones. The masses are usually amorphous, but sometimes *septarian*, *i.e.* consisting of nodules or concretions with compact crust, the interior being broken up by angular, radiating, or intersecting cracks filled with a foreign mineral.

Coprolites, *i.e.* dung-stones, are formed from the excrement of extinct fishes and reptiles.

Guano is formed from the excrement of birds.

Phosphatic nodules which have no trace of animal remains are often called coprolites.

Bone-beds are the osseous remains of vertebrates, mingled with phosphatic nodules. The bone is usually dark brown or greyish black and lustrous.

(iv) *Carbonaceous Rocks*

When wood decomposes, the oxygen, hydrogen, and nitrogen are gradually removed until almost nothing but carbon is left. Various stages in the process of decomposition under different conditions produce humus, peat, lignite, brown coal, bituminous coal, and anthracite, the latter containing the largest percentage of carbon.

Humus (see Chapter I, Section I) is the vegetable part of the soil as opposed to the strictly mineral portion.

Peat is strictly a vegetable accumulation, and occurs in all stages of consolidation from the light fibrous *turf* of the surface, in which the several plants are apparent, to the dark compact *peat* below.

Lignite consists of a mass of branches and stems of trees and plants matted together and retaining their woody fibre.

Brown coal is lignitic in character, but so far mineralised as to show no trace of woody fibre. It is easily cut and often laminated, impure and clayey.

Coal. 'Wherever vegetation has accumulated in swampy localities necessary for its preservation, coal has been formed, and hence coal is of every geological age. Its formation in the Carboniferous period, and generally, was analogous to the growth of peat. Intercepted drainage killed the forest trees in districts experiencing a temperate climate, and, as in the English fens or Irish bogs, the stumps of forest trees are found beneath the vegetable growth, which was itself a soil for plants of many kinds now imperfectly preserved. Spores of coniferous trees furnished bituminous bands. Peat, like coal, alternates with beds of clay.'[1]

Coals may be recognised by their low specific gravity (1·28), hardness of about 2, and combustibility. Anthracite is more brittle than common coal, has a specific gravity of 1·4 and a more brilliant lustre.

(v) *Ferruginous Rocks*

These are for the most part limestones in which carbonate of iron has, to a considerable extent, replaced carbonate of lime.

Magnetite, ilmenite, specular iron ore, and limonite occasionally occur in beds or in massive form, and as secondary constituents in many crystalline rocks.

Very few rocks are free from iron, but it usually occurs in small quantities, so that its chief importance is as a colouring agent,

[1] Phillips: *Manual of Geology*, Part I, H. G. Seeley, p. 475.

though ferrous carbonate, which is often present, is white when pure, and consequently does not impart any colour (*cf.* Chapter IV, Section IV). With regard to the weathering properties of iron, see Section IV of this chapter.

Clay ironstone is a mixture of carbonate of iron and clay which occurs in nodules or thin bands in shales and clays, and is brown in colour.

Blackband is a variety rich in carbonaceous matter.

SECTION III. METAMORPHIC ROCKS

Classification. However much a rock may have been changed in structure or texture by any of the agencies of metamorphism (see Chapter II, Section III), it must have been, when first formed either an original (igneous) or derivative aqueous rock, or a mixture of both.

It would therefore appear desirable to classify metamorphic rocks according to their origin. This, however, is impracticable; hence the simplest plan to adopt is to classify them according to their degree of alteration, as 'Altered Rocks' and 'Distinctly Foliated Rocks.'

ALTERED ROCKS

Quartzite (*cf.* under 'Arenaceous Rocks') may be a sandstone which, by the deposit of crystalline quartz between its grains, has been compacted into a solid quartz-rock—its conversion being sometimes the work of percolating water under ordinary conditions; or it may be a sandstone baked by intrusive igneous rock, or it may have been crushed and altered by folding movements and heat.

Quartzite must be distinguished from 'quartz-rock' or massive quartz. The latter usually occurs in veins and coarse irregular quartz crystals which interlock. Quartzites are often jointed, show signs of bedding, and appear granular under the lens—the grains being embedded in a siliceous cement which is characteristic. The surface shows a more or less vitreous lustre. The colour is usually pale grey, and is yellowish or brownish along the joint-planes. Fracture irregular to conchoidal. Specific gravity, 2·67.

In quartzites which have been crushed by folding movements the grains are often distorted, and the quartz consists, in large part, of a mosaic of small crystalline fragments of irregular shape with interlocking margins; these are called '*sheared quartzites,*' and,

when they contain white mica in parallel crystalline flakes, they become more fissile and pass into *quartz-schist.*

Lydian stone (lydite, basanite) is a velvet-black flinty jasper, but much black chert (*cf.* under 'Siliceous Rocks' above) is called Lydian stone, as are some varieties of porcellanite.

Porcellanite is a vitreous rock composed of metamorphosed clay and resembling porcelain. It is also called *porcelain-jasper*, especially when of a red colour. *Baked shale*, which is common as an alteration product along the edges of dykes, and has become hard, cannot be scratched with a knife, and is like dull porcelain, is also known as 'porcellanite.'

Spotted shale is shale full of dark spots or patches due to contact with a dyke. Garnets may be present.

Slate is the typical cleaved rock, since only fine-grained masses, in which the minute constituents are plate-like or acicular in character, can develop the structure with such perfection. The stratification, shown by 'stripes' of a different grain or colour, must be sought for in the field, since cleavage and lamination rarely correspond. The common colours of slate are blue-black, purplish, and greenish. When the cleavage planes of slates are so crowded with micaceous flakes as to present a silvery 'sheen' it is known as a *phyllite*; when it is distinctly crystalline and micaceous throughout it is termed a *mica-slate*. The two latter varieties graduate into the typically metamorphic rock, *mica-schist.*

'**Crystalline limestone** is in general stratified; it frequently alternates with gneiss and mica-schist, and sometimes retains argillaceous partings; it was therefore a water-formed deposit. Its state of granular or saccharoid crystallisation is due to changes developed since its deposition, and partly occasioned by the action of heat on contained water: this change is more obvious in the deeper-seated than in the newer calcareous deposits.

'The beds of crystalline limestone, whether distinctly stratified or not, are in general detached and limited, and so entirely enveloped in gneiss and mica-slate as to form but subordinate members of those widespread rocks.

'Though crystalline limestone is a simple rock, its aspect admits of many variations from unequal admixture with other mineral substances. Of these the most frequent are mica, talc, and steatite, the latter of which often communicates a green or mottled colour to the whole rock.' [1]

[1] Phillips: *Manual of Geology*, Part I, H. G. Seeley, pp. 377–8.

Those crystalline limestones which are suitable for ornamental architecture are termed *marbles*, and many marbles are rocks of this kind, which owe their crystalline character to alteration by intrusive masses; still, there are also many in which the crystalline structure is not due to this cause. The term marble is, however, very loosely employed, and may be generally taken to signify any rock which takes a good polish and is employed for decorative or architectural purposes.

Serpentine rock is an altered form of peridotite, massive and compact, yellow-green, dark green, purple, or red in colour, and full of veins often of a different colour from that of the mass. It has a soapy fracture and is easily cut with the knife. Some rocks called serpentine are really serpentinous limestones, while others are serpentinous schists.

Distinctly Foliated Rocks

Classification. *Foliation* has been described in Chapter IV, Section III. When a foliated rock is fine-grained in texture and divides with ease into thin sheets, it is termed a *schist*; when it is granitoid in texture and the foliation is coarser, it is termed a *gneiss*.

Schists and gneisses may be altered sediments or altered igneous masses, or again may be due to original flow and not to metamorphic action.

In schists, the foliation is but little interfered with by large crystals, while the gneisses contain compact bands or knots of crystals of felspar, quartz, etc., and, owing to the coarseness of the foliation, do not split so readily as schists.

Gneiss. This name is now generally applied to all foliated holocrystalline rocks having a granitoid texture. The chief varieties are named according to their mineralogical composition, as augite-gneiss, biotite-gneiss, horneblendic gneiss, etc.

'The *component minerals* of gneiss and granite are the same—quartz, felspar, and mica. They are mixed with the like accidents and permutations, and occasional admixture of other minerals, and are subject in both rocks to the same extreme variation in size. But these rocks differ in the mode of arrangement among their constituent minerals. The ingredients of granite are so connected together by contemporaneous or nearly contemporaneous crystallisation, that one mineral penetrates and is intimately united with

another; and we are compelled to conclude that they were not accumulated in distinct crystals ready formed, but that the minerals never had a separate existence as solids until their different geometric forms were slowly developed by crystallisation. Gneiss almost always suggests, by some degree of imperfection of the edges and angles of the quartz and felspar, and much more decidedly by the laminar arrangement of the mica and consequent minute foliation of the rock, that its materials, ready-made and crystallised, were brought together and arranged by water.

'Gneiss is essentially a mass of quartz and felspar, foliated with thin films of mica which are sometimes exposed by fracture. As in granite, the felspar is usually orthoclase, but oligoclase is sometimes associated with the orthoclase, though oligoclase is more frequent in hornblende-gneiss and protogene-gneiss; there are varieties of gneiss in which orthoclase is the only felspar. Occasionally albite is associated with orthoclase. Orthoclase varies in colour in gneiss quite as much as in granite, and is sometimes found in porphyritic crystals. The quartz occurs either in grains or small lenticular plates made up of many crystals united together. The mica may be either potash mica or magnesia mica, and occasionally both micas are found in the same rock. Sometimes the mica surrounds the crystals of felspar, giving that mineral a lenticular form. Hornblende is an important constituent in many gneisses of the West of Scotland, and chlorite and talc are found in some gneisses of Scotland, so that gneiss has often been divided into mica-gneiss, hornblende-gneiss, and chlorite gneiss.

'*Structure.* Gneiss varies in structure with the condition of the mica. In the common type mica is found in separate laminæ, dividing the felspar and quartz. But when the foliated structure is indistinct, owing to the imperfect continuity of the mica films, the rock is termed granitic gneiss and makes a transition to granite. On the other hand, the mica may be so abundant as to isolate the quartz and felspar in lenticular masses; and in section this condition gives a delicate, veined aspect to the rock. Sometimes the mica shows parallelism, giving the foliæ of the rock as regular an aspect as exogenous growth in wood; and this condition further developed imparts a platey cleavage to the gneiss.' [1]

Mica-schist. *Mineral constituents.* 'The kind of mica in mica-schist varies with the locality. In the St Gothard the soda mica paragonite is found. In some localities the yellowish-white potash

[1] Phillips: *Manual of Geology*, Part I, H. G. Seeley, pp. 370–1.

mica is rich in water, and forms the species *damourite*. The colours of the mica vary, but dark magnesia mica is most common. This mineral determines the colour of the schist, which is grey, or greenish grey, or yellow-grey, or may be brownish black.

'The quartz occurs in grains, scattered between parallel layers of mica scales. As the quantity of quartz increases, the grains become large, flattened lenticular plates, among which films of mica are diffused. Occasionally the quartz becomes so abundant as to be only separated into layers by thin films of finely divided mica, and such varieties make a transition to quartzite. The varieties which are poorest in quartz always have small grains of quartz enveloped in the laminæ of mica. The varieties of structure are similar to those of gneiss; but the crumpled wavy structure is one of its most typical modifications.' [1]

Chlorite-schist. Much less common than mica-schist. Generally fine-grained. The dark green colour is distinctive, and there are blackish-green scales on the foliation planes. It is soft and soapy.

Talc-schist is still more rare. It is generally light-coloured, pale green or white with pearly lustre. Soapy, and hardness is only 1.

Potstone, the *lapis ollaris* of the ancients, is a massive variety of talc-schist, composed of a finely felted aggregate of scales of talc, with chlorite and serpentine. It is also known as *indurated talc* or *talc-slate*.

Hornblende-schist is very common. It is usually greenish black, showing the peculiar lustre of hornblende—quite different from dark mica-schist.

Amphibolite. A rock consisting chiefly of amphibole and usually, but not always, having a foliated structure, is considered by some writers to be identical with hornblende-schist.

Epidiorite is practically a hornblende-schist, consisting essentially of hornblende and felspar, often with epidote, garnet, and sphene, quartz or biotite, and usually foliated. Being tough and hard, is well suited for roads.

Calc-schist is a schistose limestone with accessory silicates, which form lustrous specks on the foliation planes.

Granulite. A fine-grained, banded metamorphic rock (*cf.* under 'Granite,' Section I), chiefly composed of quartz and felspar and allied to gneiss, but less well-foliated and finer-grained. *Trap granulite* is a black, fine-ground rock with red spots of garnet, generally accompanying gabbro and serpentine.

[1] Phillips: *Manual of Geology*, Part I, H. G. Seeley, p. 375.

Hornfels. A fine-grained, hard, splintery, often tough and durable rock, consisting of (*a*) biotite-hornfels derived from sandstone, shale, and slate, dark brown to black, with a velvety lustre due to small scales of black mica; (*b*) calc-silicate-hornfels derived from limestone, white, yellow, pale green, and brown; (*c*) derived from andesite, basalt, or diabase, green and dark green in colour.

Eclogite is akin to glaucophane-schist, one of the amphibole schists. It consists of bright green pyroxene or amphibole with garnet, and often has a schistose structure.

Flaser-gneiss (flaser-gabbro, etc.). Igneous or gneissic rocks which have been subjected to earth pressure, with the result that the constituents become separated from each other by finer crystalline material.

Augen-gneiss (augen-gabbro, augen-schist, etc.). Igneous or metamorphic rocks showing 'eyes' or inclusions of crystals, etc., set in a finer crystalline and foliated ground-mass.

SECTION IV. ROCK DECOMPOSITION

We have seen in Chapter I, Section I (*vide* 'Agencies'), that the action of atmospheric and chemical processes on rocks and minerals has a disintegrating effect which is termed *weathering*, and in same chapter, (*vide* 'Work of Life') that this effect is increased or diminished by the action of plants and animals.

If we examine a pebble or piece of rock which has lain exposed on the ground for a long time, or if we examine the stones of ancient monuments, buildings, or walls, probably we shall see that their outer surface is decayed. If the decay is not evident to the naked eye, it will be made manifest by scratching the pebble or stone with a knife; and if we break it, we shall find the inside harder than the outside. Every such pebble or piece of stone is, in fact, undergoing decay or disintegration owing to the action of atmospheric and other agencies.

The **amount of disintegration** is partly dependent on the size of the fragment, partly on climate—particularly in regard to ranges of temperature, amount of moisture, height above sea-level, and exposure to prevailing winds.

The attack of atmospheric forces is assisted by *gravitation* where the slopes are steep enough to cause the pebbles and fragments to roll down and clash together.

Lightning striking upon the dry rocks of the mountain peaks often effects a considerable rending of their masses.

Decaying vegetation increases the supply of carbonic acid and thereby adds to the effect of the water. The roots of trees are also agents of great power acting with all the energy of wedges to drive the stones asunder (see Chapter I, Section I, 'Work of Life'). The surface soil may both assist and retard the process of decay. It retains moisture, especially when covered with lichens and mosses, and keeps the subsoil or rock damp long after rain has fallen. On the other hand, the soil impedes the erosion of decayed matter and thus prevents a fresh surface from being exposed to the weather.

Atmospheric decay. Dry air, as mentioned in Chapter I, Section I, has very little chemical effect on rocks or minerals, but moist air is far more potent, and very few rocks can stand continued exposure to it. They may gradually decay, their constituents becoming decomposed, or they may break up without any such decomposition. The action of moist air is greatly accelerated when condensed in the form of rain or dew.

Water. The effect of rain is described in Chapter I, Section I, and the effect of underground water in the same chapter and section. Ordinary water cannot dissolve more than one fifty-thousandth part of its bulk of carbonate of lime or marble, while if charged with carbonic acid it can dissolve one-thousandth part of its bulk of the same material.

The disintegrating effect of rain-water depends on the duration of the rain and the nature of the rock-surface. A smooth rock, free from pores and cracks, will throw off the water and be but little affected, but a rock with a rough surface, especially if there are cracks and crevices in it, will be more readily acted upon.

Joints. All rocks are penetrated by joints which originally are only incipient lines of fracture, but capillary attraction draws water into them with great energy and this tends to disrupt the rock.

Frost. When, however, the water in the joints becomes frozen it may expand and act like an explosive to rend the rocks, and the joints thus opened become filled with small bits of the rock and cannot close together again.

Heat. Surface disintegration proceeds comparatively rapidly when rocks which have been saturated with moisture are exposed to the action of a warm sun.

Chemical Decay. The joint lines are also the channels by which ordinary chemical decay penetrates into rocks.

Oxidation. As most rocks consist of compounds of silica with

alumina, lime, potash, soda, iron, and manganese, which easily combine with oxygen, disintegration by oxidation is common. Where protoxide of iron is present, it readily absorbs oxygen from the air and forms peroxide. If the iron be in the form of pyrite or magnetite, it may become oxidised and disrupt the mass. Felspar may be converted into kaolin and expand. Basalt when exposed to the air becomes covered with a brown crust consisting largely of oxide of iron.

Carbonation. Water which is impregnated with carbonic acid decomposes all rocks containing alkalies, and then dissolves a portion of the alkaline carbonates.

Since water dissolves carbonate of lime with comparative ease, a limestone in course of time may be entirely dissolved except in respect of the clay or other impurities it contains. In calcareous sandstones the cement of carbonate of lime may be dissolved and the rock disintegrated.

As water containing carbon dioxide decomposes felspar, granite may become a mass of clay with quartz and mica scattered through it, and thus eventually may be easily washed away.

Composition and Texture of Rocks. The process of disintegration is, however, chiefly governed by the composition and texture of the rocks. Those rocks the constituents of which are not liable to much chemical change under the influence of moisture are best suited to resist weathering, provided that their cohesive properties are sufficient to withstand mechanical disintegration.

Siliceous rocks. Rocks consisting mainly or entirely of silica are the least liable to chemical change of all kinds of rock. Silica in the form of crystalline quartz is practically unaffected by water containing acids. Silica in its non-crystalline form is slightly soluble.

Calcareous rocks if pure are easily dissolved, but if full of impurities the latter forms a more or less insoluble weathered crust; similarly, if they contain organic fossils the latter will stand out in relief, as the crystalline texture of the fossils resists disintegration better than the mechanically aggregated matrix of the rock.

Many rocks weather with a thick crust or even decay for several feet from the surface, *e.g.* granite (see below).

Igneous Rocks

'The igneous and metamorphic rocks consist in greater part of various silicates which are largely subject to external atmospheric

influences. In consequence of this, these rocks, hard and seemingly indestructible as they generally are in the unaltered state, are liable to decompose and disintegrate into soft and yielding masses. As the sedimentary strata are traceable back to the antecedent igneous rocks—these changes in the structure of the latter bear upon the composition of the former. The insoluble essential bases of both are alike—only that in the sedimentary rocks they exist free, and in the igneous rocks are usually combined. All the rocks of igneous origin consist of silica, sometimes free (quartz), but more generally in combination with the various earths and alkalies, and a few metallic oxides, forming with them a variety of silicates, amongst which the felspars very largely predominate.

'**Felspars** are essentially double silicates of alumina, and of the alkalies and alkaline earths. They contain more or less potash or soda, and form more or less stable compounds in proportion to the quantity and nature of the alkalies present. Their composition varies in consequence of the bases being liable to be in part replaced by one another; the three geologically more important varieties contain silica, alumina, potash, soda, and lime in variable proportions.

'Felspar is unable to resist the solvent action of water when saturated with carbonic acid.

Formation of kaolin. 'Exposed to the action of the weather, the felspars of the hardest granites, and of the analogous crystalline rocks, are, under certain conditions, decomposed by the carbonic acid in the rain- and surface-waters,[1] forming, with the lime and alkalies present, carbonates which, being readily soluble, are, with probably some alkaline silicates, removed wholly or in greater part by the water; while the silica set free remains mostly as an impalpable powder. The combination of silica and alumina, on the other hand, being entirely insoluble, remains combined with a portion of water which is taken up during the change, and the resultant is a white mealy powder, unctuous and plastic in water. This is a hydrated silicate of alumina, or kaolin (china-clay). This change shows the loss of a portion of the silica and of all the alkalies; while the whole of the alumina, in combination with the other portion of the silica, remains as an insoluble residue, holding a definite proportion of combined water. But, as there generally remain some portions of undecomposed felspar and a variable

[1] Or by subterranean agencies, *e.g.* heated vapours carrying fluorine and boron, or by solution of carbonic acid acting from below.

quantity of free silica, the actual composition in nature varies within certain limits.

'*Origin of clays.* Almost all the china-clays contain, with a definite hydrated silicate representing the typical kaolin, small portions of the other elements present in the original rock. This kaolin is the basis of all clays; and where the decomposed rock contains foreign elements, the clays show correspondingly varied composition. Granite and its ally pegmatite furnish the purest kaolins. Kaolin is also obtained from decomposed porphyries and gneisses.' [1]

Clays may also be formed from syenite and greenstone. Clays formed from the disintegration of felspars containing potash are free from lime; those formed from labradorite, which is the principal component of lava and basalt, contain lime and soda.

Decomposition of other Silicates. 'The decomposition is not limited to the felspars. It equally affects the other silicates which enter so largely into the composition of the more basic igneous rocks, *e.g.* hornblende, augite, olivine; and as in these rocks free quartz is generally absent, the whole mass disintegrates and decomposes. These rocks furnish by their decomposition not only kaolin, together with lime and magnesia, but also a large proportion of the peroxide of iron resulting from the peroxidation and hydration of the protoxide; while a hydrated silicate of the protoxide of iron is formed as another product of the alteration of the hornblendes and augites. It is in this way that the widely disseminated iron-peroxides and glauconite (silicate of iron) have originated.

'It is owing to the presence of these complex silicates containing lime magnesia, that the metallic oxides and diorite, diabase, melaphyre, and other basic rocks generally decompose into green and brown clays. Great bodies of these rocks are also converted into masses of soft and decayed rock, of grey-green, red, or brown colours, formerly known under the general name of "wacke." At Robschutz in Saxony a decomposed diorite is worked as a fuller's-earth, and near Florence a decomposed variety of gabbro is worked as a fireclay.

'*Serpentine*—itself an altered rock—is not infrequently more completely decomposed and changed into magnesian clays, sometimes white and at other times coloured. Some of these clays contain as much as 33 per cent. of magnesia.

[1] Joseph Prestwich: *Geology, Chemical, Physical, and Stratigraphical*, vol. i, pp. 47–49.

'*Basaltic rocks.* The alteration in the felspathic bases is very noticeable, and as these rocks, like the older greenstones, contain silicates with metallic oxides, they only furnish very impure clays.

'Other basic volcanic rocks, such as *dolerite*, *andesite*, etc., are also liable to decompose; and so also in a less degree are the trachytic lavas and scoriæ. The vitreous lavas are less liable to decompose.

'Ordinary clays are not generally derived direct from the parent igneous rock, but are *reconstructed*, especially in the later deposits, from older clay beds.' [1]

Origin of Quartzose Sands and Sandstones. 'Granites (see Section I) consist of a more or less intimate mixture of quartz and felspar, in proportions varying, on the average, from 40 to 50 per cent. of each, with 5 to 10 per cent. of mica. The quartz forms a crystalline matrix, which, as the felspar decomposes, breaks up in fine-grained granites into grains generally of small size; or, if it be of coarser grain, then into larger fragments. As decomposition goes on the whole rock loses its coherence; and, on the removal of the decomposed soft parts, crumbles down into a grit or gravel of quartz, with flakes of the mica. These being comparatively indestructible, the only further change they undergo is through wear, by which their angles are gradually rounded off and the size of the grains reduced. This takes place on shore-lines, by tide- and wave-action (see Chapter I, Section I). The result is the production of a fine quartzose, and more or less micaceous sand, such as may be seen in the many beautiful small bays on the coast of the Land's End. All the soft and soluble ingredients of the decomposed silicates have disappeared, and a simple residue of micaceous quartzose sand, with some amorphous matter, remains. When, however, as not infrequently happens, portions of the felspar resist decomposition, the sand becomes further mixed with a proportion of felspathic debris. It is from this source that the materials of the various quartzose, micaceous, and felspathic sandstones of the sedimentary strata have been chiefly derived. As in the case of the argillaceous strata, such sandstones are not always derived directly from the crystalline rocks, but are constantly *reconstructed* by denudation from the earlier sedimentary strata of the same class. In these reconstructions the only change which is effected is a greater amount of wear of the sand, and the gradual removal

[1] Joseph Prestwich: *Geology, Chemical, Physical, and Stratigraphical*, vol. i, pp. 49–52.

of all traces of felspar, which yields ultimately to the successive changes.[1]

Extent of Disintegration. 'The decomposition of *granite* is not confined to the surface, but extends to considerable depths. The process of decay is very variable, depending on the nature of the felspar, and upon climatic temperature and humidity. Moisture, or even a damp condition, is the great element in effecting decomposition, but the influence of cold is important. Thus, while the granite monuments of Egypt have remained unaltered for ages, the recent monuments of St Petersburg already show symptoms of decay. Again, in this country, some of the Cornish and Welsh granites (Lamorna, Penryn, etc.) furnish solid and enduring materials for our public monuments, while others (St Austell, etc.) are so decomposed as to form a mass of quartz grit and white clay (kaolin) that can be readily removed with pickaxe and spade.

'Over large tracts in Cornwall, France, Spain, India, Central Asia, and elsewhere the granite is thoroughly disintegrated. The depth to which decomposition extends is, however, very variable; sometimes to a few feet, at others to more than 100 feet. The decay is also irregular, some parts of the same granite resisting decomposition more than others. Hence the formation of granite blocks and "tors" (see Chapter I, Section I).

'*Graphic granite* is very liable to decompose. At Itsasson, near Bayonne, this rock is decayed to a depth exceeding 150 feet, and horizontally on the side of the hill for a distance of more than 100 feet. It forms a very fine white kaolin with free quartz.

'Some *gneisses* are also extensively decomposed, forming kaolin clays more or less pure; this is of common occurrence in Central France. Around Rio de Janeiro the gneiss has decomposed into a reddish clay from a few inches to 100 feet deep. In the Pyrenees the disintegration extends to depths of 40 to 50 feet or more.

'The *syenites* and *diorites* of Guernsey and Jersey, according to Professor Ansted, are disintegrated in places to a depth of 50 feet or more; and he states that a considerable part of the north of the island of Alderney consists of a thick bed of sand and fine gravel with boulders, the whole mass being derived from the decomposition of the greenstone rock *in situ*.

'The *ophite* (diorite) of the Pyrenees is disintegrated generally into a bright brown argillaceous mass with concentric nodules or

[1] Joseph Prestwich: *Geology, Chemical, Physical, and Stratigraphical*, vol. i, pp. 54–55.

subangular blocks of the unaltered rock remaining *in situ*, and to such a depth that the unaltered rock rarely shows in the pits or railway sections, which are 30 to 40 feet deep. This rock is of Late Cretaceous and Miocene Age.

'*Serpentine* is sometimes decomposed to a considerable depth. This is frequent in Northern Italy. In addition to the formation of unctuous clays, the change sets free carbonate of magnesia and silica, which are deposited in veins traversing the altered rock.

'*Basaltic* rocks are decomposed often to great depths, and generally give rise to impure ferruginous clay, although at times the iron has been so far removed as to leave a light-coloured clay. The grains of titaniferous iron which may be present remain unaltered.'[1]

Dykes are much liable to attack by sea-water. In the Isle of Man dykes may be seen which are more affected by this agency than the surrounding limestone.

Laterite and *Palagonite*, which are rocks of considerable local importance, are merely weathered and altered forms of volcanic rock.

Laterite is a red ferruginous porous clay, covering vast areas in some tropical countries—often consolidated into rock which is used locally for buildings and roads. It is chiefly composed of alumina and iron oxide with some manganese and titanium at times, and is formed from weathering action on basaltic and other lavas.

Palagonite is a yellow or brown rock of vitreous structure and resinous lustre, composed of more or less perfectly cemented particles of basic volcanic glass.

'The *schistose* rocks are also subject to change. A talcose schist in the neighbourhood of Pau and Bagnères is so altered that the disintegrated mass is worked as a marl for manure. Other schistose rocks have been found to pass into an impure fuller's-earth.'[1]

SEDIMENTARY STRATA

Although productive of infinitely less actual decomposition, changes in the sedimentary strata, due to the influence of air and moisture, are nevertheless of importance from the differences they often produce in the aspect of the strata, the deceptive appearances to which they give rise, and the extent of the original decalcification.

Most of the sandstones contain silicates with alkaline base, and

[1] Joseph Prestwich: *Geology, Chemical, Physical, and Stratigraphical*, vol. i, pp. 55–59.

in the sandstones of the Holy Mountain, near Heidelberg, fragments of felspar are observed partly changed into clay, and visible as white points in the sandstone.

Alteration of Colour. 'Rocks originally grey, or blue, are changed to light yellow, red, or brown. Ochreous and even blackish beds become white, and dark greens pass into browns and reds. These changes are due to the oxidisation of the metallic bases by air and moisture, and to deoxidisation by organic matter (see Chapter I, Section I). Thus some of the grey argillaceous limestones or marls of the Lias, or of the Kimmeridge, and similar argillo-calcareous strata, which imbibe small portions of water, become light yellow or brown for some distance from the lines of joint and bedding. Sometimes the whole mass is bleached; but more frequently central dark cores are left. This alteration is due to the circumstance that almost all these argillaceous limestones owe their bluish-grey colour to the presence of a small quantity of *bisulphide of iron* (iron-pyrites), or of some carbonaceous matter. The former, when exposed to the action of air and moisture, is decomposed and changed by oxidisation of the sulphur and iron into the sulphate of the protoxide of iron; and this in its turn is decomposed, the acid uniting with some of the earthy or alkaline bases present, and the protoxide passing into a hydrated peroxide. The rock consequently loses the dark colour due to the original pigment, and retains only the slight tinge due to the presence of the iron-peroxide.

'When the colouring is due to *organic* or carbonaceous matter alone, the alteration is effected by the slow oxidisation of the organic matter by the air and moisture. The organic colouring matter is thus often completely destroyed, while the resulting carbonic acid is carried off by the permeating waters, either alone or in combination as a carbonate of some substance.

'*Freestones.* This alteration, owing generally to the greater permeability of the oolitic and other freestones, extends in them to a greater depth than in the more compact rocks. In these it has generally removed the colour of the whole mass of the strata above the line of permanent water-saturation (see Chapter VII), and it is not until a depth considerably below the surface is reached that the rock is found to retain the grey colour it originally had.

'*Green rocks.* The presence of minerals with a base of iron-protoxide, as glauconite, gives some rocks a deep bright green

colour. On exposure, the silicate of iron is decomposed, the silica being set free, and the iron, taking up a further portion of oxygen and water, is converted into a hydrated peroxide. Consequently, the rock loses its green colour, and passes to yellowish brown or ferruginous. This action is very marked on the surface of the calcareous iron-ore of the marlstone of the Lias; and the brown colour of some of the oolitic iron-ores may, owing to the permeability of the strata and the consequent influence of the surface waters at depths, be due to a change of this nature. Some of the fossiliferous iron-sandstones of the Lower Tertiary strata of Kent are not improbably decomposed green-sandstones, and possibly some portions of the Red Crag were deposited originally as green glauconiferous sands.

'*Argillaceous strata*, such as the London Clay, Kimmeridge Clay, and the Oxford Clay, generally contain concretions and shell-casts of iron-pyrites which, when exposed to the air, decompose and form an efflorescence of the sulphate of iron, which ultimately passes into the brown hydrated oxide. It is to the decomposition of another small portion of iron-sulphide dispersed through beds of this class that is due the change which commonly takes place in the London and other of these clays, from dark bluish grey at depths to a light burnt-umber-brown near the surface—a change which often extends to some depth.

'*Deoxidisation*. On the other hand, the influence of vegetable matter in effecting deoxidisation is very marked, as shown in the case of a piece of lignite found in the London Clay around which the iron was deoxidised and the clay changed from a dark brown to a light fawn colour.

'*Bleached gravels*. A change of another kind takes place in iron-stained superficial gravels, such as are common in the neighbourhood of London and in the Hampshire Tertiary area. These gravels have a bright ochreous colour, caused by the presence of a small quantity of the peroxide of iron. When they form, as is often the case, moors and commons covered with heath, or here and there coated with a thin layer of peat, the organic matter carried down by the rain-water reduces the iron-salt from a peroxide to a protoxide, which the free carbonic acid present converts into a carbonate; and this salt, being soluble, is removed by the same surface-waters, leaving the upper part of the gravel colourless and often quite white. Or it may sometimes be that the humic acid in the soil removes the iron as a soluble humate. The yellow

staining of the flints is also removed, and they then present a bleached and white surface.' [1]

BIBLIOGRAPHY

ANSTED, J. T.: *Elementary Course of Geology, Mineralogy, etc.*
BAUERMAN, HILARY: *Text-book of Systematic Mineralogy.*
,, ,, : *Text-book of Descriptive Mineralogy.*
BIRD, CHARLES: *Geology: A Manual for Students.*
CHAMBERLIN and SALISBURY: *Geology: Processes and their Results.*
COLLINS, J. H.: *First Book of Mineralogy.*
FORD, W. E.: *Dana's Manual of Mineralogy.*
GEIKIE, ARCHIBALD: *Text-book of Geology*, 2 vols.
,, ,, : *Class-book of Geology.*
GREEN, A. H.: *Physical Geology.*
GWINNELL, W. G.: *Geology in Systematic Notes and Tables.*
HARKER: *Petrology for Students.*
HATCH: *Text-book of Petrology.*
LAPWORTH, CHARLES: *Intermediate Text-book of Geology.*
PARK, JAMES: *Text-book of Geology.*

[1] Joseph Prestwich: *Geology, Chemical, Physical, and Stratigraphical*, vol. i, pp. 141–3.

PART II

GEOLOGICAL OBSERVATION

In the practical application of geology to engineering, which is the subject of the concluding and major portion of this book, it is important that the geological factors should be based on the most reliable data.

In many places geological maps and descriptions can be referred to and will serve as a general guide, but whether they are available or not, the engineer must make his own observations, as local knowledge is essential in all engineering work.

Geological observation may be divided into (*a*) Outdoor Work or Field Geology, and (*b*) Indoor Work. As stated in the Introduction, the engineer is advised to leave indoor work to an expert. The method of collecting specimens is described in Section III of the following chapter, and should be adopted when collecting specimens for analysis or other kind of examination.

CHAPTER VI

FIELD GEOLOGY

All geological observation must be carried on in the most accurate and careful manner possible. Every fact which throws light on the area observed must be carefully noted and the record must be full and accurate. The observer should train himself not to jump to conclusions, but to view every bit of evidence with regard to the nature and structure of the rocks which are concealed from view, and must learn to interpret rightly such facts as are patent, without minimising their value or too greatly exaggerating it.

SECTION I. GEOLOGICAL SURVEYING

Most engineers have been trained in ordinary land surveying, either for civil or military purposes, and should therefore be able to attain proficiency in geological surveying very readily. But before undertaking such work they must have some knowledge of the first principles of geology. While the summary given in Part I should suffice for a start, they will do well to elucidate any doubtful points by reference to one of the standard text-books.

Preliminary Study. Before going into the field it is necessary to endeavour to locate the stratigraphical formations likely to be encountered. Geological maps and sections of most parts of the world where the engineer is likely to go are generally available, and with the aid of these a preliminary study of the district where work is to be done can be made.

A **geological plan** consists of a plan or plans of the surface features, in which are shown the boundary lines of each bed or stratum exposed in the area, and as much information as possible with regard to the structural characters of the district. It may be necessary to prepare two or more plans of the same area in order to show the various formations.

A **geological section** not only gives the outline of the surface features, but also the geological formations and structural characters as far as they can be traced, *e.g.* dips, faults, thickness of strata, unconformability, curvature, etc.

To a certain extent a geological section must be considered an ideal one, inasmuch as some of the details of what is below the surface of the ground must remain uncertain; but the indications obtained in the process of geological surveying will afford a sufficiently accurate basis for filling in the details of the section. It will often be necessary to prepare several sections in different directions across a given area.

In order to gain experience in observation in the field, it is a good plan to go over some area for which accurate geological plans and sections are available. A definite section line should be followed across country and observations made and recorded, and subsequently compared with the plan and section. At first many indications which an experienced field geologist would note may be missed, but by comparing one section with another it will be possible to follow out the reasoning by which the recorded map and section were established.

Fossils. The most important guide to the identification of formations is *Palæontology*, or the study of fossils. Every formation has its corresponding fossils.

Since, however, space does not admit of a chapter on this fascinating subject, the engineer must have recourse to the standard works on the subject.

Equipment. After providing himself with the best available geological maps and sections, and if possible a list of fossils to be looked for, the engineer must go out into the field and make his own observations. For this purpose a certain amount of *equipment* is essential, *e.g.* a hammer with chisel end, compass, clinometer, Abney's level, pocket-lens, bag and belt, tape-measure, and notebook. In other words, the engineer should add a geological hammer to his usual survey outfit. A good topographical *map* is essential.

Observations to be made are as follows:—

I. To trace the geological structure, with a view to identifying the formation, noting the following:—

(*a*) Boundary lines, nature and thickness of all strata or groups of strata; curvatures, important joints, faults, etc.

(*b*) Position of igneous rocks, intrusions, dykes, lodes, coal-seams, and mineral deposits, as well as contacts between igneous and sedimentary rocks.

(*c*) Boundaries of metamorphic rocks, recording nature of metamorphism, amount of alteration, etc.

II. To determine the nature of the rocks, noting age, mode of occurrence, composition, and description of clays, stones, ores, etc.

Preliminary Reconnaissance

Preparation of Plan. Having secured, or made, a topographical plan of the area, in which the surface features are shown by contour lines or hachuring, it should be used for recording geological observations.

A *tracing* of the portion of ground over which observations can be made in a day or two should be fixed on a piece of cardboard with gum, etc., along the edges. The observations made in the field should be entered on the tracing, and transferred to the plan at the end of each day's work.

Contours and Boundary Lines. The boundary lines of each bed or stratum exposed in the area must be entered on the tracing. These boundary lines are the lines where the lower margins of the strata cut the surface of the earth, and the boundary line of any given stratum coincides with the outcrop of the stratum below it.

The relation of the boundary lines of strata to contour lines is as follows :—

(1) When the strata are horizontal, the boundary lines coincide with the contours. This is obvious.

(2) When the strata dip towards a hill, the boundary lines are less winding than the contours.

The truth of this can be seen if we imagine the dip increased until the strata are vertical, for the boundary lines would then become parallel straight lines.

(3) When the strata dip away from a hill, the boundary lines are more winding than the contours.

This is true so long as the dip is less than the slope of the hill, but if it is greater, the boundary lines wind in a reverse way to the contours.

When *tracing boundary lines*, the observer should first look for any natural sections or artificial exposures such as cliffs, quarries, road and railway cuttings, etc., and selecting these as his principal points, he will locate them on his map and then make a traverse of the intervening country, noting all the geological features.

Preliminary Traverses. In making such traverses, all the main streams and tributaries should be followed, as well as salients, ridges, and escarpments. Roads, paths, and other lines which

divide the area should also be followed; if there is a coast-line it should be traversed. In working along these lines the ground on either side should be examined, so that the whole area will be covered.

When there is little change of surface feature, the boundary lines will be found higher up than would be expected, owing to the soil and rocks moving down to a lower level.

The points to be noted in making traverses are general indications of the geological structure and nature of the rocks, as particularised in the introductory remarks to this section.

It is all a matter of experience, and the beginner cannot expect to recognise at first all the indications which an experienced field geologist would note. In obscure country such as marsh, moors, grasslands, etc., it will often be necessary to go further afield in order to obtain clues.

Indications of nature of rocks. While making the traverses, every indication of the nature of the rocks met with should be sought for. All natural and artificial exposures should be examined and specimens taken.

It may be necessary to dig through soil and subsoil at times, and when doing so, weathered portions of rock should be looked for.

The *soil* and *subsoil* afford valuable indications of the nature of the rocks from which they have been derived.

Vegetation also assists, *e.g.* oak grows well on clay, while fir-trees are found on light sandy soils.

A rapid reconnaissance of this kind will enable the engineer to gain a general impression of the topography and geological structure of the district, and afford an opportunity of judging how best to undertake a systematic survey.

Systematic Survey

The **general field procedure** should be as follows:—

As noted above under 'Observations to be made,' all outcrops, boundary lines of stratified and igneous rocks, cliffs and escarpments, etc., should be sited as accurately as possible on the plan. Descriptions of the shape and extent of the outcrops should be entered in the field-book; also of the nature, thickness, strike, and dip of the strata; height above sea-level, and any notable topographical features. Both plans and sections or profiles of outcrops, cliffs, and escarpments should be drawn in the field-book, giving compass-bearing, height, and length in each case.

The positions of any fossiliferous beds should be noted and description of the more abundant fossils given.

In the case of igneous rocks, their boundary lines and position of dykes, sills, or lava should be noted.

Faults may be seen on any natural exposure, such as faces of cliffs or sides of ravines. Their displacement, vertically and horizontally, strike, and dip should be entered.

Fossils. If the engineer has been able to study palæontology, and has provided himself with descriptions of fossils, he will find them of great assistance in his observations. Fossils may be collected while the survey is being made, but it is preferable to note the positions of fossils while surveying, and afterwards examine the fossiliferous beds carefully and collect fossils, samples of rock, and minerals at one time.

Fossils will generally be found below the outcrops of beds in which they occur. As representative a collection as possible should be made.

Plotting. First of all, a table of the geological formations found in the district should be drawn up. It is desirable that each formation should be distinguished on the plan by a particular colour, and where a formation is divided into beds or horizons of importance, each of these should be given a different colour, or distinguished by some conventional sign.

It is usual to plot first the traverses along streams and ridges, and then the boundaries of formations, and finally the subdivisions of formations.

Sections. In running a section, a line should be selected which traverses those parts of the area which are geologically most important, and which show the relationship of the different formations to one another, and also one which is, as nearly as possible, at right angles to the strike of the beds ; if necessary, the bearing must be changed from time to time to fulfil these purposes.

If an accurately contoured map is not available, the inequalities of the surface of the ground must be recorded in the usual way by means of theodolite and level and chain, or if great accuracy is unnecessary, by pacing and Abney's level or clinometer. All outcrops, artificial or natural exposures, wells or borings, dips, faults, etc., should be noted on the section.

When *plotting sections* the vertical scale should be the same as the horizontal, as otherwise the inclination of the beds will be distorted.

The method of drawing sections will be familiar to engineers.

SECTION II. STRUCTURAL CHARACTERS OF ROCKS

It has already been pointed out in Section I that, while making the geological survey of an area, all possible indications of the nature of the rocks should be looked for and noted down. The structural characters of rocks are dealt with separately in this section for the sake of convenience, but it is not meant that a separate examination of the district must be made on this account. The structural characters of the rocks should be noted while the geological survey is being made.

Referring to Chapter II, we note that the first question for consideration is whether the rocks met with are igneous, aqueous, or altered, and in forming our conclusion we must bear in mind that igneous rocks are usually crystalline and aqueous rocks are very generally fossiliferous. We must remember, however, that some altered rocks are crystalline, and that some igneous rocks, composed of fragmentary volcanic materials, are stratified or bedded. Again, the jointing of igneous rocks and the lines of foliation and cleavage in altered rocks must not be confused with lines of stratification in aqueous rocks (see Chapter II).

The structural characters of **igneous** and **metamorphic** rocks need no further reference beyond that given in Chapter II.

As mentioned in Chapter II, the changes which occur in **aqueous** rocks are (i) stratification; (ii) inclination; (iii) curvature; (iv) joints; (v) dislocation. For convenience we will take (i), (ii), and (iii) together; as regards (iv), joints, see Chapter II.

Strata and their Inclination

Principle of Stratification. It is obvious that every geological formation must be newer than the formation which underlies it, and older than the formation which overlies it, except in the case of inversions; and, consequently, it has been possible to draw up a definite order of stratigraphical sequence, which holds good throughout the world, although gaps occur here and there.

This law of continuity of strata must be firmly impressed on the observer, who should not be misled by the temporary absence of a particular bed or beds in any of the sections he has observed. He must look out for alterations of strata, overlap, unconformable strata, etc. (see Chapter II, Section II), and by comparison of the various sections observed he will be able to deduce the regular order of stratification in the district which he is surveying.

Dip and Strike (see Chapter II, Section II). Strata are said to dip

when they are inclined; the *direction* of the dip is the point of the compass towards which the strata slope, and the *amount* of the dip is estimated by the size of the angle which the layers make with the plane of the horizon. For example, the dip may be 40° to the south, or 60° to the north-east, and so on, the limits of variation of dip being the horizontal and the perpendicular. The direction of the dip is ascertained by means of a pocket-compass, and the amount of dip with a clinometer. The dip may be stated by the incline of 1 in a given number of units of length; thus a fall of 1 in 100 corresponds to an angle of 6°. The opposite term to dip is *rise*; if the beds dip to the west they rise to the east.

The *strike* of a set of beds is defined to be the plane at right angles to the direction of dip, on the course of a horizontal line on the surface of inclined beds; it coincides, therefore, with the line of outcrop when the surface is horizontal. Consequently, the edges of inclined strata, viewed in the line of their strike, will be level, whilst a section at right angles will exhibit the true direction and maximum amount of slope of the strata. If, then, a bed dips due east, its strike is due north and south. Through knowing the strike, we do not necessarily learn either the direction of the dip—because it may be to either side of the line—or of its amount; yet to ascertain the true dip it is requisite that the line of strike be determined, inasmuch as the direction and amount of dip will vary with the section obtained. Thus, if the strike be due N. and S., then all the sections, except the one at right angles, will give a false dip; if the dip be 45° E., then the variations in dip will be from W. and E. to N. and S., and from 45° to 0°.

Strike and bedding planes. The strike is usually more or less straight, but if the bed is bent or folded, the strike necessarily curves or changes from point to point. It may also be described as the horizontal line along the bedding plane of the rock.

It is necessary, therefore, to make sure that the bedding plane is a true one and not merely a joint-plane. The bedding planes of thin and flaggy sandstones and limestones, etc., can easily be distinguished. Those of massive rock, such as conglomerate, are often indicated by layers of other material which may be harder or of different texture or colour, or by layers of fossils.

Observing the strike. As long a surface of the bedding plane as possible should be exposed, and a horizontal line along the outcrop should be marked with pegs or stones or scratched on the rock, and the bearing—which is the strike—observed.

All observations should be checked by repetition.

Measurement of dip. 'In observing a dip, the plane of the graduated arc of the clinometer must be held parallel to a vertical rock-face on which the beds appear exposed, and the distance between the eye and the rocks should be reasonable, in order that the straight-edge may appear coincident with a considerable length of the dipping strata. The instrument is tilted until this edge appears to lie along some well-marked line of stratification ; the plummet or index then points to an angle equal to the angle of dip observed. Several observations are desirable as checks to one another ; any evidences of lenticular or current-bedding (*cf.* Chapter II, Section II) must be noted, and the compass-bearing of the face of rock utilised must also be observed.

'The dip thus found is very probably only an apparent dip, and is less than the true dip, which runs in some other direction. Two or more observations taken near to one another will settle this point. Thus, where there are two dips seen on different walls of the same quarry, or in closely adjoining quarries, and where these are evidently not due to mere local slippings or to the very common creep of the higher beds down the slope of a hillside, then the direction and amount of the true dip can be found by the simple geometrical method of Mr W. H. Dalton.

'The directions of the walls, or rock-faces, on which the dips are seen are determined with the compass, and two lines are drawn to represent them on paper, giving the angle *r a b*. Should one dip in the actual quarry-sections incline towards *a* and the other away from *a*, one of the lines drawn must be produced, so that the dips represented in direction by the lines *a r* and *a b* both either incline towards or away from *a*.

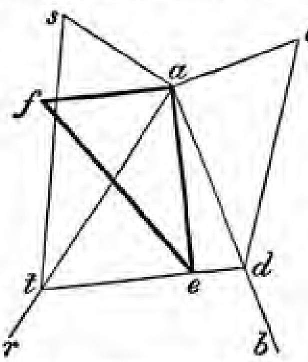

Fig. 25. Measurement of dip.

'Draw *a c* perpendicular to *a b*, and of any convenient length, say, for greater accuracy, about 3 inches ; and draw *a s* perpendicular to *a r* and equal to *a c*. From *c* and *s* draw lines making with *a c* and *a s* respectively angles equal to the complements of the observed angles of dip and cutting *a b* and *a r* in *d* and *t*. Then the angles *a d c* and *a t s* represent the angles of observed dip along the directions *a b* and *a r* respectively.

'Join *d t*; this line represents the strike of the beds. *a e*, drawn from *a* perpendicularly to it, gives us the direction of true dip. Draw *a f* perpendicular to *a e* and equal to *a c* or *a s*; join *f e*. The angle *a e f*, when measured with a protractor, gives the amount of true dip.

'The matter is clear if the three triangles *a s t*, *a c d*, and *a f e* are imagined as bent up so as to stand perpendicularly to the plane *a t d*, which remains horizontal. The points *s*, *c*, and *f* coincide, and a plane laid upon the dipping lines *s t*, *f e*, and *c d* will represent truly a surface of one of the strata observed in the field, when both the apparent dips were inclined away from *a*. *d t* is a horizontal line in this surface, and is therefore the strike; the line *f e* now perpendicular to it, and also in the same surface, represents the true dip both in compass-bearing and in inclination to the horizon.' [1]

Observing dip and strike. Observations should be made at points where the rocks are clearly undetached. On walls of deep gorges and on steep cliffs special care is necessary as, in such cases, the outcrops are often bent or warped. True anticlinal folds should be distinguished from variations of inclination due to unequal pressure, etc.

Calculating the Thickness of Strata. By knowing the upper and lower boundaries of a stratum and its average dip, one can readily determine approximately the depth at which it will be found under any given spot, and its thickness. In fig. 26 let A B represent the level surface of the outcrop of a bed, the thickness of which, and the depth of its lower surface below the point B, it is desired to ascertain; the dip having previously been observed to be 30°, and the distance A B = 300 yards. Then B C at right angles to the horizon is the depth, and B D at right angles to the dip will be the thickness of the bed.

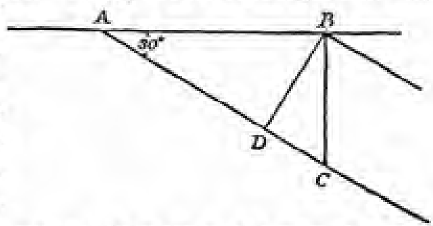

FIG. 26. Calculating thickness of strata.

Then in right-angled triangle A D B,

$$\sin A = \frac{BD}{BA}. \quad \therefore \quad BD = \sin A \times AB$$

or the thickness of the beds $= \sin 30° \times 300 = \frac{1}{2} \times 300 = 150$ yards.

[1] G. A. S. Cole: *Aids in Practical Geology*, 7th ed., pp. 5–7.

Again, in right-angled triangle A B C, the angle at A and length of A B are known, so that

$$\tan A = \frac{BC}{AB}. \quad \therefore \quad BC = \tan A \times AB$$

that is, BC or depth of C below B = tan $30° \times 300 = 173$ yards nearly.

Any two terms being given in either of the equations, the third can be obtained for each.

When selecting a point for measuring the thickness of strata, care should be taken to avoid faults or isoclinal folds where the strata are likely to be repeated.

Outcrop and Strike. As the strike is always at right angles to the direction of the dip, it must continually change with the latter. It must not, however, be confused with the outcrop, which is the line where any particular formation cuts the surface.

As explained in Chapter II, Section II, the strike must coincide with the outcrop when the surface of the ground is quite level, and also when the beds are vertical. At all other times they do not coincide, but the outcrop wanders to and fro across the strike according to the changes in the angle of inclination and in the form of the ground.

Curvature. If any of the upper beds which have come to the surface, in any district, are found to be setting in again and dip in the opposite direction away from their line of strike, an anticlinal is indicated ; and similarly, when the beds dip inwards in opposite directions a synclinal may be expected. The above is true whether the beds are faulted or not.

Overlap. This may be detected, even when there is no section which displays it, by the boundary lines of the two beds gradually drawing nearer to one another and the outer or lower one disappearing beneath the inner or higher bed.

Unconformity (*cf.* Chapter II, Section II). There will usually be a considerable difference in inclination, and the boundary lines will generally draw near to one another at a considerable angle.

Dislocation

See under *Dislocation* in Chapter II, Section II.

The **presence of a fault** may be anticipated from the following :—

(1) The abrupt ending of an outcrop, or the want of continuity of definite bands or beds.

When a bed passes under another unconformable one the outcrop of the first bed will terminate abruptly, but in this case the line of junction will be a wavy line following the dip and surface features of the newer unconformable bed, whereas the line of a fault will be a straighter line.

(2) An abrupt change in the strike due to an abrupt change in the direction of the dip.

Changes in direction of dip and strike often occur in beds which are not fractured, and at times the change is very sudden, but in such cases the changing dip forms a curve where the direction changes, whereas if the beds are fractured by a fault there will be a sharp angle at the point where the direction of dip changes.

(3) A considerable change in amount and direction of dips of the same bed in adjacent sections.

Change in direction of dip may indicate flexure (*cf.* Chapter II, Section II), but when there is change in amount of dip as well a fault is indicated.

(4) The presence, between outcrops of any two formations, of a formation not in its normal position; or the absence, between outcrops, of a formation which is usually present.

This may be an indication of either a fracture or an unconformity; other indications must be looked for.

(5) When a bed fails to appear at the place where, from its dip as previously observed in section, it was expected; or, the appearance of a bed at a place where, from its dip, it was not expected.

This is an indication of either a fault or a flexure.

Tracing Faults. The faults which are seen on cliff faces or other exposed sections are very often comparatively small ones. The larger faults can seldom be actually seen, although their presence can be detected by surface indications. One reason for this is that along the fault-lines of larger faults the walls of the fracture are subjected to great crushing force which causes them to crumble away, and thus the opening becomes filled with debris and the fault is concealed. Again, later deposits frequently cover the older rocks, and thus the dislocations among the latter are hidden from view.

SECTION III. DETERMINATION OF ROCKS

Selection of Specimens

Specimens must be gathered *in situ*, for if taken from talus, road or rubbish heaps, they are very misleading. If too large to be carried away, a sketch or photograph, giving dimensions, should be made, and chips taken from different parts of the rock.

Some of the points to be noted in choosing specimens are mentioned below under the headings 'Igneous Rocks,' 'Aqueous Rocks,' etc.

Soils and subsoils may be collected in tins. Subsoils should be taken from an excavation some two feet or more below the surface of the soil.

Crystals are to be found in cavities and open joints, while *rock specimens* must be taken from larger masses in order to obtain unweathered surfaces. Weathered crusts may also be collected in order to show the effect of atmospheric action. The difference in colour is well shown in clay blocks with bluish hearts and brownish surfaces.

All specimens should be wrapped and labelled in the field, and dated.

Easily Distinguishable Characters

It must be clearly understood that the characters described below and referred to in Table II are only such as can be easily detected in the field. In all important or doubtful cases the specimens should be examined at home.

Structure. The various kinds of structure referred to in the table are:

Crystalline.	Vitreous.
Compact or Homogeneous.	Cleaved.
Foliated or Schistose.	Earthy.
Fragmental.	Concretionary.
Granular.	

Crystalline includes all types in which crystalline texture can be detected by the eye, but the minuter forms, such as cryptocrystalline, etc., are included under *Compact*.

Compact or *Homogeneous* includes all close-grained and lithoidal rocks.

Foliated or *Schistose* rocks are those of a distinctly foliated character (see Chapter V, Section III).

Fragmental (see Chapter IV, Section III) includes breccia, conglomerate and volcanic agglomerates, tuffs, etc.

Granular. This term refers rather to texture than structure (see under *Structure*, Chapter IV, Section III).

The remaining terms, Vitreous, Cleaved, Earthy, Concretionary, are described in Chapter IV.

Hardness. In estimating the hardness of a rock the pocket-knife must be used freely, as in the case of minerals. A rough scale for testing the hardness of the latter is given in Chapter III, Section I, which is also applicable to rocks. The angle of a steel hammer, drawn across the face of a rock, often gives similar information to that obtained by means of a pocket-knife.

All rocks tend to have a hardness a little below that of their principal constituents (see Chapter IV, Section IV).

Streak. While the specimen is being scratched to ascertain its hardness, the streak or colour of the powder produced by scratching should also be observed.

Feel. May be *rough*, as trachyte; *smooth*, as mica; *unctuous*, as talc, steatite, and serpentine (slightly); or *meagre*, when the surface seems to rub off in powder under the finger as chalk.

Smell. This is apparent in some limestones containing hydrogen as well as carbonic acid, which, when rubbed, smell strongly of hydro-carbon; also in some varieties of quartz. Some clays have an earthy smell when breathed upon.

Effervescence. If a drop of dilute nitric, sulphuric, or hydrochloric acid in the proportion of 1 part acid to 5 parts water be applied to the fresh fractured surface of a rock, it will cause rapid effervescence if the rock is a pure carbonate of lime, slow effervescence if the rock is partly composed of carbonate of lime, but none at all if the rock is a sulphate or silicate.

Colour and Lustre (see Chapter IV, Section IV). The colours of weathered fragments and fresh-fractured surfaces should be carefully noted and the lustre, if any, of the latter should be observed.

The various kinds of lustre recognised by experts in the case of minerals are given in Chapter III, Section I, and the same terms are applicable to rocks, but it will generally suffice, for the purposes of the rough outdoor examination under consideration, to note whether the freshly fractured surface is or is not lustrous.

Fracture. The usual forms are given in Chapter IV, Section IV.

Table II. Easily Distinguishable Characters of Rocks

I. Compact Structure

No. of Speci-men	Texture	Hardness		Specific Gravity	Streak	Efferves-cence	Colour		Lustre	Fracture	Feel and Smell	General Remarks	The Rock is probably
		Scale	Scratched by Knife				Fresh Fracture	Weathered Crust					
1	Close-grained	0·5 to 1·0	Easily	..	..	None	Dark grey, brown, or blue. Sometimes red, yellow, or white	..	..	..	Earthy smell when breathed on	Soft and crumbling	Some clay rock, *e.g.* mudstone, shale, or fire-clay, or decomposed felspar rock, *e.g.* orthoclase-porphyry or felsite
2	Close-grained or cleaved	0·5 to 1·0	Easily	..	White	None	As No. 1	..	Earthy	..	As No. 1	Harder and fissile	Shale or clay-slate
3	Close-grained or granular	1·5 to 2·0	..	2·2 to 2·4	White	None	White, yellow, or reddish	..	Dull or glistening	Even	..	Occurs in beds or veins (possibly fibrous); slightly soluble in HCl	Gypsum; *cf.* No. 41
4	"	"	..	..	..	Brisk	White or yellowish	..	..	Friable and crumbling	Soils fingers	..	Chalk marl, or some powdery form of limestone
5	Close-grained	3·0 to 4·0	..	2·5 to 2·7	White	None	Pale to dark green, or reddish or blotched or clouded	..	Resinous	Splintery to sub-conchoidal	Feels soapy	Edges subtranslucent; insoluble	Serpentine
6	Close-grained or oolitic or earthy	3·0	..	2·6 to 2·8	"	Brisk	White or bluish grey, yellow, brown, or black	..	Dull, vitreous to earthy	Even	..	Soluble in acid	Some form of limestone or chalk; *cf.* Nos. 27 and 30
7	Close-grained or granular	3·5 to 4·5	..	2·8 to 2·65	Powder of streak slowly effervesces in hot acid		Yellowish white or pale brown	..	(in fall)	Even	..	..	Dolomite; *cf.* No. 31
8	Close-grained	3·0 to 4·0	..	3·0 to 3·9	Yellow to brown	None	Dark brown to dull black	Brown or blood-red	Sub-metallic	Fibrous	..	Occurs in nodules, or beds usually with shale	Brown iron ore or clay iron-stone
9	"	3·0 to 4·0	..	3·0 to 3·9	Cherry red	None	Reddish	..	"	Sub-conchoidal	..	Occurs in nodules, or beds	Hæmatite

10	Close-grained or schistose	..	..	2·55	..	None	White, grey, yellowish or bluish	White	..	Splintery	..	Rings under hammer; partly soluble in hydrochloric acid	Compact phonolite, felsite, or dacite
11	Close-grained	..	..	2·9 to 3·2	..	Slight on weathered crust	Black or dark green	Yellow or brown	..	Conchoidal	..	..	Basalt, andesite, aphanite, epidiorite, or amphibolite
12	„	6·0 to 6·65	With difficulty when fresh	2·55 to 2·7	White	None	White, bluish grey, yellow, lilac, brown, red	White or yellow	Vitreous	Even	..	..	Felsitic rock
13	Very finely granular or horny	7·0	..	2·5 to 2·9	Metallic of steel	„	White, reddish yellow to brown or black	..	Conchoidal	..	..	..	Silica, jasper-hornstone, flint, or chalcedony
14	Fine-grained						Same	as No. 34					Diorite or diabase
15	Granular						Same	as No. 35					Dolorite
16	Fine-grained						Same	as No. 36					Andesite
17	„						Same	as No. 37					Orthoclase-porphyry or quartz
18	Close-grained	..	With difficulty	2·8 to 3·0	..	Slight on weathered crust	Greenish	..	..	..	..	..	Gabbro or hypersthene rock
19	Granular	..	Not at all	..	..	Slow	Various	..	..	..	..	Quartz grains in calcareous matrix	Calcareous sandstone
20	„	..	Not at all	..	..	None	White	..	..	..	..	Quartz grains	Sandstone
21	Close-grained	..	With difficulty	..	..	None	Greenish black	..	Vitreous or horny	..	..	..	Hornblende rock
22	„	..	With difficulty when fresh	2·6	..	None	Grey	..	..	Even	Feels gritty		Trachyte
23	„	..		2·6	..	..	Pink-brown	..	..	..	..	..	Porphyrite
24	„	1·5	With ease	2·7	White	None	White or grey	..	Pearly to dull	Uneven	Soapy	..	Talc or steatite
25	„	..	With difficulty	..	White	None	Yellow-green	..	Resinous	..	..	..	Apatite phosphorite
26	„	..	Not easy	..	..	None	..	..	..	..	..	..	A silicate of some kind
27	Granular	..	Not at all	..	..	Slow	Various	..	..	Even	Slaty odour when breathed on	Soluble in acid	Argillaceous limestone; *cf.* No. 6
28	Earthy	2·0	..	..	Shining	..	Greenish grey	..	..	..	..	Powder mixed with water, does not form a paste	Fuller's-earth
29	Vesicular	..	..	2·3	..	..	Grey	..	Glistering	..	..	Insoluble	Pumice

TABLE II—*Continued*

II. CRYSTALLINE STRUCTURE

No. of Specimen	Texture	Hardness		Specific Gravity	Streak	Effervescence	Colour		Lustre	Fracture	Feel and Smell	General Remarks	The Rock is probably
		Scale	Scratched by Knife				Fresh Fracture	Weathered Crust					
30	Fine-grained	..	Easily	..	..		Same	as No. 6	..	..	..	..	Some form of limestone; *cf.* No. 6
31	Fine-grained or granular	..	Easily	..	..		Same	as No. 7	..	..	..	..	Dolomite; *cf.* No. 7
32	Granular	..	Easily	..	White	None	Tinted	..	Dull or glistening	Even	..	..	Alabaster or anhydrite
33	Fine-grained	..	With difficulty	..	..	..	Greenish tint	..	..	..	Feels heavy	Composed of only one mineral	Amphibolite
34	"	..	With difficulty	2·6 to 2·9	..	Slight on weathered crust	Green	Brown	Dull	..	..	A white mineral and a green one—insoluble	Diorite or diabase; *cf.* No. 14
35	Granular	..	With difficulty	3·0	..	Slight on weathered crust	Grey	Yellowish or brownish	..	..	..	Striated felspar and dark crystals (augite)	Dolerite; *cf.* No. 15
36	Fine-grained	..	..	..	..	Slight on weathered crust	Dark grey	Yellowish or brown	..	..	..	Finely crystalline matrix with porphyritic felspars	Andesite; *cf.* No. 16
37	"	..	With difficulty	..	..	None	..	Bleached, argillaceous	..	..	..	Crystals of orthoclase	Orthoclase-porphyry or quartz-porphyry; *cf.* No. 17
38	"	..	With difficulty	..	..	None or very slight	Various, usually light coloured	..	..	..	..	Distinct crystals of quartz, fresh and weathered	Granite, quartz-porphyry or syenite
39	"	..	With ease	..	White	Rapid	White or tinted	..	Vitreous to earthy	Conchoidal	..	..	Crystalline limestone or marble
40	"	2·0	With ease	2·2	"	None	White or tinted	..	Vitreous	Conchoidal	..	Soluble in water	Rock-salt
41							Same	as No. 3					Gypsum
42							Same	as No. 26					A silicate of some kind

43	Granular	..	Not at all	..	..	None	..	..	Glassy on fracture surface	Curved	Slightly rough to touch	Associated commonly with schists or slates	Quartzite
44							Same	as No. 18					
45							Same	as No. 53					
46							Same	as No. 38					
47							Same	as No. 58					
							III. Foliated Structure						
48	..	1·5	Easily	2·7	..	None	White, grey, dark grey, or green	..	Glistening to dull pearly	..	Feels unctuous	If massive, is probably soapstone	Talc - schist, chlorite - schist, mica-schist, or foliated serpentine
49	Fine-grained or cleaned	..	Not so easily	..	White	None	Dark grey	..	..	Splintery or slaty	Earthy smell when breathed upon	May contain crystals of pyrites, etc.—insoluble	Argillaceous schist or clay-slate
50	Fine-grained	..	Not so easily	..	..	..	Dark grey	..	Silky	..	..	..	Phyllite
51	Fibrous (fine)	..	Easily	..	..	..	..	..	Silky	..	..	Fibres easily separable	Asbestos
52	,, (coarse)	..	Harder	..	..	..	Greenish to white	..	Vitreous	..	..	..	Actinolite-schist
53	..	Nearly 7	..	..	..	..	Grey	..	..	Splits with some difficulty along the laminæ	..	..	Quartzose variety of mica-schist, quartz-schist, or gneiss
54	..	..	..	..	..	..	..	..	..	..	..	Lenticles of quartz separated by folia of mica and plates or grains of felspar	Mica-schist or gneiss
55							Same	as No. 10					Phonolite or clinkstone
56							Same	as No. 38					Rhyolite
							IV. Vitreous Structure						
57	..	..	With difficulty	2·4	..	None	Brown or grey	..	Vitreous	Conchoidal	..	..	Obsidian or pitchstone
58	..	7	..	2·6	..	None, or very slight	White or tinted	..	Waxy on fracture surface	,,	..	..	Flint or hornstone if black or grey; *cf.* No. 47

TABLE II—*Continued*

V. FRAGMENTAL ROCKS

No. of Specimen	Fragments			Cementing Material			General Remarks	The Rock is probably
	Shape	Size	Composition	Coherence	Effervescence	Colour		
59	Rounded	Pin's head or less	Quartzose	Sometimes by pressure only	None	..	Sometimes no matrix discoverable	Sandstone
60	Thin laminæ which may be broken into flakes, but do not become rounded	..	..	..	..	..	..	Particles of mica
61	Rounded	Pea or less	Quartzose	..	..	..	..	Pebbly sandstone, fine conglomerate, or grit
62	"	Pea to walnut	..	..	..	..	..	Gravel or conglomerate
63	"	Man's head or larger	Quartzose	..	..	..	..	Coarse shingle, conglomerate or boulder-bed
64	Rounded or subangular	Various	Calcareous organic debris	..	..	..	..	Limestone
65	Subangular	Various	Quartzose with minute fragments of other minerals	..	..	..	..	A variety of sandstone named after the mineral
66	"		Quartzose	..	..	..	..	Breccia or brecciated conglomerate
67	"	Various	Quartzose, loosely aggregated	..	..	..	..	Scree material or drift-stuff
68	Angular and irregular	Large	..	..	..	..	..	Coarse volcanic agglomerates

Igneous Rocks

We have seen in Chapter II, Section I, that both plutonic and volcanic rocks may be derived from the same rock magma. Thus, in a mass of igneous rock, the centre may be crystalline and the margin more or less glassy, while there will be border-line rock with an intermediate constitution. Samples should therefore be taken from all portions of the rock-mass.

The junctions of igneous rocks with other masses are often difficult to detect, especially on grassy slopes, etc.

In passing from the margin, which may often be decomposed, towards the centre, a good look-out must be kept for foreign patches, which may or may not have modified the nature of the general mass.

Granite.[1] Quartz may be easily distinguished by its clear glassy granules without cleavage. The dark micas are most common, but muscovite occurs. Biotite crystals with dull edges often resemble fibrous hornblende, but may be identified by the lustre of the basal planes. Orthoclase may be recognised by its large, rather tabular crystals.

Syenite. Not so common as granite or quartz-diorite. Resembles hornblende-granite, but quartz is absent, or scarce, in true syenite. Sphene often occurs in small, hard, yellow crystals.

Diorite. The essential constituents are hornblende and plagioclase. In *hornblende-diorite* there is little or no quartz, the hornblende being usually green, but may be brown or yellow. In *mica-diorite* biotite is an important ingredient, and is always brown or yellow. In *augite-diorite* the augite is generally green.

Orbicular (cf. *corsite*, a variety of diorite, cf. Chapter V, Section I), banded, or foliated structures may occur. Hornblende-gabbros resemble diorite, but contain more basic felspar and occasionally olivine.

Quartz-diorite. In addition to hornblende and plagioclase, contains a considerable amount of quartz, is generally grey in colour, but may be reddish from red felspar. Resembles granite—a great deal of the stone, known commercially as granite, really being quartz-diorite.

Gabbros. Have the same composition as dolerites, but the crystals are coarser. In *olivine-gabbro*, the yellowish-green, glassy olivine may be distinguished from the larger and less transparent pyroxene. In *norite*, the diallage is replaced by hypersthene, which has a coppery lustre.

[1] In each case reference should be made to Chapter V, Section I.

Pyroxenites differ from gabbros and norites, to which they are closely allied by the absence of felspar, and from peridotites by containing olivine.

Peridotites may be recognised by their dark colour, high specific gravity (3·0 and over), and generally poikilitic structure. The 'lustre mottling' caused by the smooth and shining cleavage surface of hornblende and augite being dotted over with dull blackish-green spots of olivine, is characteristic.

Porphyry. This general term includes granite-porphyry and quartz porphyry in the Acid Group of hypabyssal rocks, and orthoclase-porphyry and elæolite porphyry in the Intermediate Group. Rocks with a porphyritic structure, *i.e.* with scattered crystals of larger size in a finer-grained ground-mass, *e.g.* diorite-porphyry, augite-porphyry, greenstone-porphyry, are often called porphyries, but the term is better restricted to rocks of intrusive origin. Being hypabyssal or dyke rocks, they occur in the form of dykes, usually on the edge of deep-seated masses of plutonic rocks such as granite, syenite, diorite, etc., while the margins of the latter rocks often assume a porphyritic structure; hence porphyritic granite is intermediate between granite and granite-porphyry.

Porphyries are distinguished by (i) their mode of occurrence; (ii) the characteristic porphyritic alkali felspar.

Granite-porphyries are distinguished from syenite-porphyries by the presence of quartz. They are exceedingly common.

Quartz-porphyry contains porphyritic crystals of quartz, which appear in hand-specimens as small rounded, clear greyish vitreous blebs, also felspar crystals usually dull and cloudy and larger than those of the quartz. The ground-mass is usually grey, green, reddish, or white.

Porphyrites are distinguished from porphyries by long phenocrysts of plagioclase felspar in lieu of orthoclase. They correspond with gabbros and norites as porphyries do with granite, syenite, diorite, etc.

Dolerites. Hornblende may be seen occasionally with the lens, also the glancing surfaces of ophitic augite. The felspars are rod-shaped and typically dark-coloured. In *diabase*, calcite can often be detected with the eye, and fragments of the rock commonly effervesce in acid.

Rhyolites. The ground-mass, usually glassy or cryptocrystalline, is fairly hard when fresh, but when acted on by the atmosphere or by volcanic vapours it becomes softer. It is usually pale in colour,

but may be reddish, pinkish brown or yellowish brown, or white, and the fractured surfaces are often conchoidal.

Phenocrysts[1] are of orthoclase, clear glassy sanidine, with granular quartz, biotite, augite, or hornblende. Fluidal and banded structures with spherulites are common.

Trachytes. As in the rhyolites, the ground-mass is typically pale. The proportion of glass to crystals is less than in rhyolites, and banded and spherulitic structures less common. The fractured surface is rather rough.

Basalts occur as lavas, sills, and dykes. They exhibit every form of structure from glassy tachylite to holocrystalline, when they tend to pass into dolerites. Porphyritic, vesicular, and amygdaloidal structures may be present.

Tuffs. These for the most part appear compact when freshly fractured, but the weathering of joint-surfaces causes the different ingredients to stand out clearly. Hand-specimens of the weathered surfaces should always be collected, and the whole mass should be sketched in the field.

The compact beds formed from the finer ashes can only be determined by the microscope.

Aqueous Rocks

Sands should be collected as dry as possible, and from places where they will not have been sorted out by the action of wind. The chief difficulty is to clean them for observation. The mud should first be rubbed off, as far as possible, with the fingers, and the sands should then be washed. Where consolidation appears to have commenced, any signs of cementing material should be sought for. It will often be necessary to clean the sands with acid.

Where magnetite is present, as often occurs in the case of sands derived from igneous rocks, it can be detected by a magnet.

In all cases of doubt the engineer will do well to send specimens of the sand to a chemist.

Grits, Sandstones, Gravels, and Conglomerates. In all cases the individual constituents should be released by attrition, and the cementing matter examined chemically if possible. The gleaming cleavage-surfaces of calcite are unmistakable; silica and barytes can be identified fairly easily. In crystalline sandstones, crystal faces of quartz can be seen. The amount of rounding of the constituents of gravels and conglomerates should be noted.

[1] The larger crystals.

Clays and Shales. The plasticity of clays and their sectility when dry is well known. The proportion of silica and iron pyrites, etc., in clays can be found by washing. The clay should first be broken up into small lumps and well dried.

In *shales* their fissility is a distinguishing feature. The older rocks are often darker than those formed later.

Marls will effervesce when treated with hydrochloric acid, owing to the presence of carbonate of lime.

Bauxite as a rule has been formed from decay of igneous rock rich in alumina. Like clay, it is sectile and adheres to the tongue, and is compact.

Limestones. The colours vary a great deal, but the hardness (about 3) aids detection. Some hard dark limestones resemble quartzite, sandstone, or even basaltic lava, but the knife leaves a clear white scratch which settles the question.

Sand grains, glauconite, flakes of mica, and tremolite are often found in limestones.

In *shelly* limestones the shells may be of calcite or aragonite—the latter is harder and will scratch the surface of calcite crystals.

In *oolitic* limestones distinct spherical or ellipsoidal bodies can be seen, and usually form the larger proportion of the mass, being similar in colour to the ground-mass. *Pisolitic* limestones are similar to oolitic but coarser, and the ellipsoidal bodies are often flattened.

Rock-salt often contains earthy and ferruginous matter, which is left when the salt is dissolved in water.

PART III

APPLIED GEOLOGY

THE importance to the engineer of a knowledge of geology having been referred to in the Introduction, it only remains to add that Part III on *Applied Geology* deals with the application of geological knowledge to the various branches of engineering detailed in the chapters which follow.

CHAPTER VII

WATER-SUPPLY

'The several sources of supply known to hydraulic engineering science are to be regarded merely as stages of the various courses pursued by water in its passage from the rain-clouds to the ocean. Whether precipitated through the atmosphere as rain, or flowing over the earth's surface as stream or river, or percolating the soil and rocks beneath, the motion of water is to be explained according to the same uniform physical laws.' [1]

SECTION I. RAINFALL AND EVAPORATION

Rainfall

The sources of water supply are springs, wells, rivers or catchment areas, and the basis of investigation into the capabilities of such sources is an accurate estimation of the rainfall upon the areas from which water is to be derived.

Rain (see Chapter I, Section I) on leaving the clouds is undoubtedly pure water, but in passing through the atmosphere, especially after a long drought, it absorbs oxygen, nitrogen, carbonic acid, some ammonia and nitric acid, and also brings with it particles of matter floating in the air. After rain has been falling for some time the air is cleared, and the rain-water comparatively clear of foreign substances and gases.

The particles floating in the air, in the open country, are chiefly organic, but in or near manufacturing towns various other substances are taken up, and when rain is collected after falling on the roofs of houses it will be further contaminated.

The **quantity of rain** chiefly depends on (1) Climatic conditions; (2) Physical conditions.

Climatic Conditions. Rainfall in 'the major climatic regions of the world' [2] is briefly as follows:—

Equatorial region. Rainfall heavy from 70 to 80 inches upwards. Rather less in areas cut off from the influence of the sea.

[1] Tudsbery and Brightmore: *Principles of Waterworks Engineering*, 3rd ed., pp. 10–11.

[2] Cf. *Modern Geographical Ideas*, by L. Dudley Stamp: 'An Outline of Modern Knowledge.'

Tropical region, where vast areas of grasslands lie between equatorial forests and hot deserts. Rainfall from 70 to 80 inches on forests' edge to 15 inches on deserts' border, and as much as 200 in wettest parts.

Tropical monsoon. Lands of India, Indo-China, and South China. Rainfall varies from 500 to 5 inches.

Hot deserts, on poleward side of regions with tropical climate, occur generally on west side of land-masses. Little or no rain.

Mediterranean. Rainfall varies from 10 to 40 inches.

Warm temperate. S.E. States of U.S.A., greater part of China, S.E. coast-lands of Australia and South Africa, Uruguay, and S.E. Brazil. Moderate rainfall throughout year.

Cool temperate. British Isles, coast-lands of British Columbia. Well-distributed rainfall throughout year.

In the temperate zone more rain falls on the western coasts of large continents than on the eastern side or in the interior, but in the tropics more rain falls on the eastern side. Rain falls on more days in the temperate zone, but more rain falls in the tropics. Most of the moisture in the air comes from the tropics, and consequently in England it is usually the S.W. winds which bring moisture.

Physical Conditions. 'Where the prevailing winds are warm, and heavily charged with moisture, by crossing a large extent of ocean, the rainfall on the first high ground encountered by them will be heavy. The moist air, rising to the altitude of the hills, expands in volume and is reduced in temperature, in accordance with the adiabatic law[1] for the expansion of gases and vapours. The cooled air cannot hold in suspension so large a quantity of vapour as before, and the latter is deposited in the form of mist, rain, hail, or snow. The rainfall of a district is likely to be small if the prevailing winds traverse a wide expanse of land before reaching it, or if they come from a place of low temperature to a warmer district of no greater elevation. Under such circumstances the air is generally in a suitable state for absorbing additional moisture.'[2]

Variation of rainfall. The amount of water the air can

[1] If no heat is supplied to the air during expansion, then the air loses an amount of heat equivalent to the external work done, and the temperature falls.

[2] Tudsbery and Brightmore: *Principles of Waterworks Engineering*, 3rd ed., p. 38.

contain depends on temperature and pressure. If either of these is decreased, moisture will be deposited; if either is increased, the tendency to deposition will be lessened.

A rain-bearing wind blowing against the sides of a hill is compressed and the pressure is increased, but the wind is also deflected into a higher part of the atmosphere, where pressure and temperature are less than at the point of impact.

If there is a valley on the reverse side of the hill or ridge, the wind, having expanded at the top, will deposit more moisture on this reverse side than on the far side of the valley beyond; *e.g.* the rainfall on the east side of the Western Ghâts, which run north and south behind Bombay, is very much greater than on the west side. The water supply of Bombay is obtained from reservoirs on the eastern slopes of the Ghâts and carried down through tunnels.

Similarly the rainfall usually increases with the *elevation*, and in England it is customary to allow for an increase of from 1 to 3 per cent. of the rainfall per 100 feet above the rain-gauge—the lower figure being adopted for wet districts. Much appears to depend upon the elevation of the country with regard to the region of the rain-clouds, which may be said to extend to about 3000 or 4000 feet above sea-level.

Estimation of Mean Annual Fall. In connection with the supply of water obtainable from gathering grounds of natural and artificial reservoirs, as well as for purposes of compensation to millowners, etc., it is important to ascertain the mean annual rainfall.

Observations over an extended period are very necessary.

Rain-gauges must be placed in as many situations in a district as will cover the various elevations and conditions met with.

Rainfall varies day by day, month by month, and year by year. Hence, to obtain reliable results the average of between 30 and 40 years should be taken. But if the latter results are not obtainable, except at one or two places, or not at all, an average for each rain-gauge must be taken and the best available conclusion arrived at. If the gauges are placed at equal intervals a general average can be obtained, but if not so placed, the readings for each gauge should be multiplied by the area represented.

If there is at least one or more long-established gauge in the area the records of which have been carefully noted for a long time, it will be of immense service as a check on the newly established gauges.

A difficulty arises in the case of a heavy fall of *snow*. This may

either be blown away from the mouth of the gauge, or it may melt more quickly over the gauge, thereby giving a much higher record than is warranted by the true fall.

Maximum and Minimum Fall. When the mean fall at any place is known, the following rough rules may be adopted to give an approximate idea of other particulars of rainfall :—

(1) The excess above the mean in the wettest years may be taken at 33 per cent., and the same for the defect for the driest years.

(2) The three driest consecutive years may be taken at 80 to 85 per cent. of the mean. Terms of three consecutive dry years have been found, at the Greenwich Observatory, to occur at intervals of about twenty-two years.

(3) For the greatest fall in 24 hours, in the case of a mean fall of 20 inches, take 16 per cent. of the mean ; for each increase of 4 inches, decrease 1 per cent. up to 60 inches ; beyond 60 inches it remains stationary at 6 per cent.

Evaporation and Absorption

Effect on Water-supply. Evaporation and absorption are intimately connected with water-supply as regards (1) the evaporation of rain as it falls on the ground and is temporarily retained there ; (2) the evaporation from surfaces of lakes, reservoirs, and other bodies of water ; (3) the absorption by vegetation of a large proportion of the rainfall—part being retained in the body and fibres of the plant or tree, and part being evaporated from the leaves. This absorption depends on the nature and amount of the vegetation.

Evaporation from the surface of the ground depends on the rate of rainfall, the physical and geological formation, the nature of the surface, and the drainage. The maximum evaporation occurs in sandy plains and on flat spongy ground with an impervious subsoil. The minimum occurs on impermeable surfaces.

Loss. A common rule is to allow one-third of the rainfall as drained into streams and rivers ; one-third as percolating into the ground, reappearing in springs ; and one-third lost by evaporation and absorption by vegetation. But this is not correct, for with increased rainfall the loss is decreased, and when the rainfall is less, the temperature is higher and the humidity less. In the dry season the loss by evaporation increases very much. In England this loss varies from 9 to 19 inches, and during the summer months may be taken at one-eighth to one-fifth of an inch per day.

'Generally, upon permeable soils or upon steep and impervious land, the loss by evaporation is small. If, however, in permeable soils the surface of saturation is, owing to the physical features of the locality, situated near to the surface of the ground, evaporation takes place actively under favourable atmospheric conditions.'[1]

Evaporation from Surfaces of Water. The discrepancies between the records of careful observers have been almost incredible—probably owing to the small scale on which experiments were made. 'In England the loss from evaporation has been estimated as equivalent to a depth of about 3 feet from the surface of reservoirs; whereas from reservoirs in India it has been reckoned as a depth of 4 to 6 feet over the whole area in a year (*cf.* Molesworth's *Pocket Book*, 23rd ed., p. 319). In the United States it has been calculated that the evaporation from surfaces of water ranges from a minimum of about 18 inches in a year on the North Pacific coast, up to a maximum of about 100 inches on the Southern Plateau. The annual evaporation at Melbourne from a water surface has been found to amount to 40⅝ inches; whilst in South Africa it is 39 inches at Port Elizabeth on the seacoast, and at Van Wyk's Vley Reservoir, in the interior, it reaches 80 inches.'[2]

Dry Weather Flow. Of more importance, however, than the mean annual evaporation is the evaporation during the dry season of the year, when reservoirs are being taxed to their utmost capacity, and when, therefore, the elements of loss have to be more closely watched. Mr Burnell, in his *Rudiments of Hydraulic Engineering*, says: 'The experience derived from the use of reservoirs on canals appears to indicate that, during the summer months, it is necessary to allow for an evaporation ranging between one-sixth and one-eighth of an inch per day.' In an important matter like this it is perhaps advisable, in order to be on the safe side, to allow for daily loss during the dry season of not less than one-fifth of an inch.

SECTION II. UNDERGROUND AND SURFACE WATERS

UNDERGROUND WATER

The surface of the earth is divided into ground surfaces and water surfaces. Rain falling on water surfaces adds to the volume of the water which is continually being reduced by evaporation.

[1] Tudsbery and Brightmore: *Principles of Waterworks Engineering*, 3rd ed., pp. 49–50.

[2] L. F. Vernon-Harcourt: *Sanitary Engineering*, p. 23.

Rain falling on ground surfaces will run off if the surface is entirely impervious, or, subject to losses by evaporation and absorption into vegetation, will to some extent percolate into the ground if the latter is at all pervious. A ground surface which, though otherwise impervious, is so jointed and cracked that water can penetrate underneath, must be considered pervious for present purposes.

Water Table. The level at which water stands in pervious ground is known as the *plane of saturation*, *surface of saturation*, or *water table*. The lowest level at which the plane of saturation stands in the material or strata underneath the ground is at or near the level of the sea. Below that line the rocks are always saturated, and the plane of saturation never sinks much below the level of the sea. The height to which rocks are saturated above the level of the sea depends on their porosity, the rainfall, and the distance from the sea.

Slope of the Water Table. The rain-water falling on the surface of the land 'still continues, under the action of gravity, to seek lower levels, pursuing those routes in which it experiences the least resistance to its downward motion. Generally speaking, this direction is vertical through soil and subsoil, until its progress is checked by encountering the great body of water that saturates the subterranean regions at depths depending upon local circumstances. Here the motion is not arrested, but its direction becomes inclined at a certain angle, which is determined by the resistance opposed to the flow by the strata at the place in question. The inclination of this subterranean water-slope changes from point to point according to the geological formations traversed. In permeable rock, such as chalk [1] and gravels, the slope is naturally flat; in sandstone it is less so; whilst in compact grits the angle of inclination is large in just such degree as the impervious character of the rocks requires greater hydrostatic force to overcome their resistance to the passage of the water. The absolute level at any point of the slope also varies according to the volume of water which, contributed by the rainfall, seeks a passage to the ocean.

'Thus there extends in all directions a *surface of saturation*, or, as it is sometimes termed, *plane of saturation*, occurring always where the descending waters assume a definite surface slope, in accordance with ordinary hydrodynamical laws.' [2]

[1] The permeability of chalk is chiefly due to the fissures that traverse it.

[2] Tudsbery and Brightmore: *The Principles of Waterworks Engineering*, 3rd ed., p. 12.

Saturation and Imbibition. In addition to the water contained in the rocks at saturation level, there is a certain amount of *water of imbibition* to be reckoned with. This is due to capillary action, the rocks above the line of saturation soaking up or imbibing water from below. This moisture is well known in certain building stones as 'quarry water' or 'quarry sap' (*cf.* Chapter I, Section I, 'Frost,' and Chapter VIII, Section I, 'Quarrying,' and Section III, 'Seasoning').

As soon as this water of imbibition is removed by evaporation from above, it is replaced by capillary action from below. To illustrate saturation and imbibition, take a block of chalk and place it in a basin of water. That portion of the block which lies below the surface of the water will be entirely saturated, every crevice and hollow, large and small, being filled with water. The upper portion of the block will also become damp by capillary action, and will contain a considerable quantity of water of imbibition.

Now, if we bore a hole in the block straight down from the top nearly to the bottom, water will stand in this miniature well at the saturation line—which is of course level with the surface of the water.

We will next gently pour some water over the block while it is still immersed in the basin of water; some will run off and some will soak in, and gradually make its way downwards till it reaches the saturation level. Near the outside of the block it will easily find its way into the surrounding water, but inside it will temporarily raise the saturation level, so that the water in the miniature well will stand at a higher level than before, but eventually it will sink to the original saturation level.

If the whole of the material of the earth were pervious, like our piece of chalk, the water table would fluctuate to and fro a little above the level of the sea, according to the amount of rain falling from time to time on the earth's surface. But the earth is composed of permeable and impermeable strata occurring in patches. Hence the water table varies from point to point. To every basin of stream, river, or lake there is a surface of saturation (*cf.* fig. 40). Moreover, the true surface of saturation may be obscured by surface flow (*vide* 'Conditions of Flow').

Capacity of Rocks for Water. The amount of water, either of saturation or imbibition, which any rock will contain depends on its composition and texture. The looser the texture, and the more

numerous and larger the cracks, the greater the quantity of water the rock will contain when saturated; but the rock which takes a great deal of water to saturate will not necessarily contain a large quantity of water above the line of saturation, because the cavities between its particles may be too large for capillary attraction to act. Thus a coarse loose sand will contain a large quantity of water of saturation, but it nevertheless makes a very dry soil, because, in the first place, the water can very readily make its way downwards through it, and because, secondly, capillary attraction is weak owing to the large size of the spaces between the grains.

Rocks vary greatly in the quantity of water they retain, in the way in which they retain it, in the relative facility with which they absorb or part with it, and in the degree of accidental interruption that can interfere with the free course of the water beneath the surface. Thus sands, if loose, allow water to percolate freely through them; if hardened, they conduct water very badly or not at all; if broken, they offer natural channels, permitting a very perfect but partial transmission. So limestones, under certain circumstances, are good conductors, and under other circumstances very bad conductors, of water: and this is governed by the nature of the rock, its condition, its position, and generally by those facts observed and described by the geologist. Even clays, although generally tough and quite impermeable, retaining water to any extent, are sometimes broken by permeable joints, and sometimes mixed with so much sand and lime as not to be absolutely close.

Sands and *Gravels* may be considered the most open of the different kinds of rocks, but both require careful examination if we would discover their true condition. Thus many sand rocks, although themselves loose and containing much water with which they would readily part, have undergone a partial consolidation, or are traversed by a multitude of crevices, and sometimes by systems of faults parallel to each other filled up with clay, quartz, or oxide or iron, and crossed by others at right angles to them. The whole mass of rock is thus divided into compartments or cells which have little communication with each other, and if one such compartment is drained by pumping, others at a distance are not necessarily affected. When part of a rock of this kind is covered with gravel, little difference might be anticipated; but if this surface-gravel covers up and conceals boulder-clay of a stiff and tenacious character—and this is by no means uncommon in various parts of England—the compartments above alluded to will be

very differently supplied with water in various parts of the same district.

Loose sand rocks, alternating with bands of marl and not intersected by impermeable bands, such as form the great mass of the New Red Sandstone series in the middle and south of England, usually allow water to percolate freely to their base, the marl beds forming mere local interruptions, and retaining the water at the surface only so long as it is running towards some natural vent. Harder sands and sandstones, such as the Millstone Grit, form an almost impassable barrier for water, and conduct it to some other more permeable rock.

Clays when of considerable thickness and extent do not allow water to pass downwards into the earth, and often by their level and easily smoothed surface retain large pools and sheets of water, to the great injury of the soil. When there is a natural fall to the sea, however small, there is always a possibility of greatly improving the condition of such land by drainage, while springs of water are neither required, nor if required would they be easily found without sinking. It may happen—and the geological structure of the district would show whether this is likely or not—that the clay covers up permeable and very wet beds which, if borings were made, would rise to the surface in artesian wells. On the other hand, it may happen that by opening a way into the lower beds the surface-waters would be drained off.

Calcareous or *Lime rocks* differ a good deal in their containing power with reference to water, and much doubt has long existed as to the true state of such rocks in particular cases. They may be divided into two groups—the one partaking more or less of a spongy nature, and the other hard and semi-crystalline. The Oolites offer a kind of intermediate condition. The first of these groups is illustrated by chalk, of which the soft upper beds are exceedingly porous and absorbent of water. The lower beds of chalk, though not so soft as the upper, are usually, when penetrated by sinkings, found to be exceedingly wet, and a large quantity of water is yielded freely, though the replacement seems to take place but slowly. In addition to the ordinary sources of water in the mass of the rock, there is no doubt of the existence of numerous fissures and crevices, and frequently large cavities, in chalk and all other lime rocks, and these are often filled with water at considerable pressure.

Igneous rocks in which joints or fissures are numerous, or whose

top layers are decayed, may hold a good deal of water. Volcanic fragmental rocks consisting of partly stratified ashes, etc., may be water-bearing. Schistose rocks often hold water in decayed portions or crevices.

Water-bearing Strata. As strata of various ages are exposed at many places, permeable strata may occur at any depth.

'*Drift*, consisting of the debris of rocks carried down and deposited by flowing water in valleys and depressions in the ground, and sometimes on the lower slopes of hills, having been washed down by rain from the higher ground, is very irregular in thickness, and often discontinuous. The porosity of the drift depends on the nature of the materials of which it is composed, which are usually gravel and sand, but sometimes consist of less permeable materials brought down from the adjacent hills.

'*Alluvial deposits* are very similar in their origin to drift, but they are more regular and extensive; they are usually composed of materials brought from a greater distance, often filling up ancient lakes and river-beds, and they consist mainly of sand, gravel, and stones, together with clays and marls. Sometimes these permeable strata form the surface layer, and receive their supply of water by the direct percolation of the rainfall; but they are often partially overlaid by an impervious stratum, under which the ground-water flows for considerable distances. *Sand* furnishes the most porous stratum, being capable of absorbing from one-third to nearly one-half its volume of water; whilst gravel and sand can contain from one-quarter to three-tenths their volume of water. Numerous wells have been sunk into these upper permeable strata for supplying water to large towns in the United States.

'The *Chalk* is the principal water-bearing stratum for a considerable part of the southern portion of England, with its good thickness and large outcrop, absorbing 30 per cent. of its volume of water on the average, whilst the *Greensands* furnish large volumes of water, more uniformly distributed throughout them than in the Chalk; and both these formations yield good supplies to wells sunk into them.

'The *New Red Sandstone* or *Trias*, though less extensive in area in England than the two above-mentioned strata, traverses the more rainy western districts, stretching from the Channel on the south coast of Devonshire to the Solway Firth, and therefore may be regarded as quite as suitable for wells. Moreover, although wells have to be sunk to a considerable depth in the New Red

Sandstone to reach water, the volume is abundant when found, and the water is less hard than that from the Chalk. This stratum, known as Trias abroad, extends over considerable areas in Europe, and also for long distances in North America.

'Other *sandstones* yield large quantities of water proportionate to their extent, outcrop, available rainfall on them, and porosity, which ranges from at least 28 to 7 per cent. in volume in the sandstones of the United States, according to their compactness, the porous Potsdam and St Peter sandstones having been largely resorted to for deriving water supplies from wells.

'*Limestones*. Water is also drawn from wells sunk in the Oolitic, Lias, and Magnesian Limestones, both in England and North America, but not with the same certainty and facility as from sandstones, since limestones only yield water when extensively fissured, and the underground flow is liable to be obstructed by faults.

'*Dip, Outcrop*, and *Slope*. The absorption of rainfall by stratified, water-bearing strata at their outcrop is largely affected by their dip, their freedom from a surface covering of an impermeable nature, and the flatness or depression of the ground. A considerable dip facilitates the descent of the water into the stratum along the interstices between the successive layers, but if continued for some distance causes the stratum to descend to too great a depth below the surface. The inflow of the rain is dependent on the permeable outcrop being free from obstruction at the surface by an impermeable layer of overlying drift, and the rain is adequately retained for percolating into the porous stratum when falling on fairly flat ground, and still more on a valley or depression, whereas it would be liable to flow away down a steep slope, and be to a great extent lost to the permeable stratum.' [1]

Yield of Water. Tables showing the absorbent power of various rocks as deduced from laboratory experiments are given in various works on Building Construction, which show that the amount of water absorbed by various rocks is very variable. While compact sandstones and limestones absorb but a small amount, soft sandstones and oolites absorb a large quantity, and quartzose sands absorb still more. But the full power of absorption of a rock, which includes both the water of imbibition and of saturation, does not represent its water-bearing value. Loose sand or a well-jointed sandstone transmits water with the greatest ease; but the presence

[1] L. F. Vernon-Harcourt: *Sanitary Engineering*, pp. 40–41.

of any clayey material greatly reduces the transmitting power. Clay absorbs water freely but transmits none ; chalk absorbs water freely but transmits very slowly.

Laboratory experiments, moreover, to a great extent ignore the joints and fissures usually found in rocks, which admit water freely and transmit it with almost equal ease. The water-bearing value of strata is in direct ratio of capacity of saturation, and in inverse ratio of power of imbibition.

SURFACE-WATERS

'The **surface of saturation** ordinarily coincides with the "free level" of the subterranean waters at every point in the district, although in synclinal basins overlaid by extremely impervious formations this is not necessarily the case. In a district the geological structure of which is of a compact and impervious nature, the surface of saturation is often situated at no great depth underground, and may at times, when the rainfall is heavy, become raised until it coincides with the land surface, such a condition resulting evidently from the permeability of the land being barely adequate to meet the demands of such increased quantity of water for a passage through it. The land is then said to be "waterlogged."'[1]

Conditions of Flow. 'There are in general two conditions of which the immediate result is the establishment of flow upon the surface.

'*Case I.* When the surface slope of a considerable tract of land is less than the hydraulic gradient required to force the entire volume of water through the earth as rapidly as it falls upon it, the surface of saturation of the district rises above the surface of the land, until a hydraulic gradient is formed adapted to the circumstances of the case, and part of the flow takes place over the ground. The "hydraulic surface," as the free surface thus formed may be conveniently designated, does not differ much from the ground surface, because the water flowing above ground is comparatively free from frictional resistance, and a slight fall is enough to produce considerable velocity, and to effect discharge off the surface as fast as the rain falls upon it.

'In the special cases of rain falling upon frozen ground, or falling very heavily, the resistance of the surface to the passage of water through it may be so high as to prevent any considerable portion

[1] Tudsbery and Brightmore: *The Principles of Waterworks Engineering*, 3rd ed., pp. 12–13.

of it from penetrating the earth, and abnormal flow may be established upon the surface, although the true surface of saturation is at the time situated at some depth beneath. Those who have had experience of severe tropical rains, or of floods caused by the sudden melting of large accumulations of snow, must have been astonished to observe the current and the depth of water which may prevail temporarily over wide areas of land into which ordinary rainfall disappears at once.

'A similar effect is produced when permeable material has accumulated in hollows on more or less impervious rock with a sloping surface. Rainfall in the rocky surface is absorbed by the permeable accumulation, and reappears at its lower edge on the surface of the rock; this a casual observer might take to be the level of the surface of saturation, whereas the real saturation level may be much lower..

'When the surface of saturation is high, the smallest depression in the land may be sufficient to cause it to issue therefrom, since the water-slope in any direction is determined by the facilities afforded to the passage of water in that direction. Any hollow below the surface of saturation presents to the water in the adjacent ground a course of diminished resistance which is naturally taken advantage of. In proportion to reduced resistance the surface of saturation becomes flattened, until, in the hollow, it issues above the ground as a true hydraulic surface.

'*Case II*. When, at any place, the surface-slope of the land is of higher inclination than the hydraulic gradient required by the flow of the percolating subsoil waters through the rocks, the surface of saturation naturally issues above the ground in the manner described in Case I. Illustrations of this action frequently occur in the streaming vertical faces of sandstone quarries, and in the marshy areas often found on steep hillsides. Some of the water that enters every ditch is contributed in like manner from the adjacent subsoil.'

'The rills on every hillside, no less than rivers and lakes, owe their origin and maintenance to such causes; and it is due jointly to the high position of the surface of saturation and to their undulating character that districts of hard and impervious geological structure lend themselves so readily to yield "surface-water"—that is to say, water which, after falling upon the earth, is almost at once directed by its own gravitating impulse to flow in channels on the surface of the land.'

'**Forests** have an important effect in acting as regulators which retard the flow of the rain into the streams, thus tending to prevent excessive rise of the latter after storms.' [1]

Dumb wells, absorbing or **blind wells,** are sometimes sunk through impervious rocks into permeable strata, to carry off surplus water, and may be used to replenish the underground supply, especially where it is largely drawn upon.

SECTION III. SPRINGS AND WELLS

SPRINGS

When water falls from the clouds in the form of rain or snow, sinks into the ground and percolates until it reaches an impermeable stratum, appearing again at the surface at a lower level, the outgush is called a *spring*. The general conditions under which springs are met with in Nature are necessarily most varied, dependent as they are on the geological structure of the locality, the alternation and inclination of pervious and impervious strata, and their endless contortions, dislocations, and faults. Water-bearing strata are such as are of an open, porous, or absorbent nature, and overlie other strata of an impermeable quality, the latter serving to retain the water in the former.

Ordinary Springs. *Pervious* on *Impervious*. The simplest case under which springs are met with is where a pervious stratum overlies an inclined impervious one, as in fig. 27, the rain falling upon

FIG. 27. Spring at outcrop of permeable stratum.

the surface of the former being delivered at S as a land or shallow-seated spring.

If the impervious substratum be depressed into a hollow or basin, the water will necessarily accumulate in the same, and the lower part of the porous stratum will become permanently saturated. Fig. 28 illustrates such a case, A B S being the *line of saturation*; and inasmuch as the water is sustained partly by capillary attrac-

[1] Tudsbery and Brightmore: *The Principles of Waterworks Engineering*, 3rd ed., pp. 13–16.

tion, it will be seen that this line need not necessarily be horizontal.

It would at first sight appear strange that the water does not rather ooze out as a sand-soak along the junction of the impervious with the pervious bed, than make its appearance at certain places only on this line, and then in the form of continuous gushing streams. This, however, is explained by the fact that on the

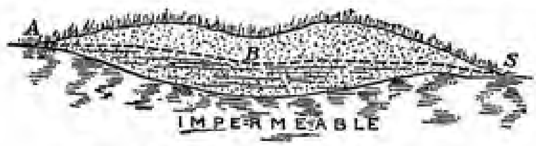

FIG. 28. Hollow collecting water.

surface of the impermeable bed numerous irregularities exist similar to those on the exposed surface of the land, and these conduct the water in definite channels and courses. Rents and fissures acting as subterranean drains assist in the concentration of the flow of water at certain points.

Pervious between two Impervious Beds. Springs are sometimes found at the lower outcrop, C (fig. 29), of a permeable bed, A,

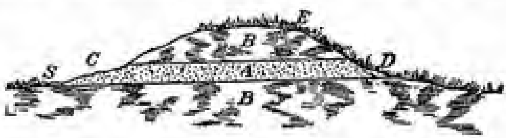

FIG. 29. Spring arising from water falling on outcrop.

lying between two others, B B, which are impermeable. The supply, however, is limited to the rainfall on the basset or exposed surface of higher outcrop, D, and as much of the drainage from the upper impermeable stratum, D, as flows down the sides of the hill and is intercepted by the stratum A. Where the strata are inclined and dip inwards from a hill-slope, a pervious bed between two impervious beds will hold more water than when the strata are horizontal.

The *outlet of a spring* is often so obscured by debris that the spring issues below its natural outlet. If the spring is to be used for water-supply the debris must be cleared away—thus obtaining additional 'head,' and the natural outlet can then be deepened.

Intermittent Springs. Where the overlying pervious stratum is comparatively shallow and of small extent, the springs issuing from it will generally be of an intermittent character, being limited by the variations of the rainfall; but, on the other hand, where it is of considerable extent and depth it acts as a natural storage reservoir, and the rain falling at intervals on the upper surface is delivered with a uniform flow. Friction and capillary attraction, acting in opposition to gravity, are the chief agents in bringing this about.

Syphon action. There is a class of intermittent springs the phenomenon of which is attributed to an action similar to that of the syphon. In fig. 30, B is a permeable stratum lying on an

FIG. 30. Syphon action.

impermeable one, C, and having a layer of an impermeable material above it. The layer, B, may for a moment be conceived as a tube. Rain falling on the basset, E F, will penetrate and descend into the pervious stratum, B, and will accumulate in the subterranean reservoir, C, until it attains to a level sufficient to overflow at G, appearing in the form of a spring at S. If the part S G C of the impervious stratum be regarded as a syphon tube, it will be understood that the water which has accumulated in the basin will be drawn over the ridge in the impermeable bed until the water-level has been lowered to a point at which the syphon will cease to act, and water will not again issue from the spring until the reservoir has received a supply sufficient to bring the syphon again into action. A well-known example of such a case may be seen beside the road leading from Buxton to Castleton.

Bournes. It sometimes happens that a permanent spring issues at a certain point generally low down in a valley. At intervals of a few years it suddenly bursts out farther up the valley, and continues to flow for some time, when it again ceases as suddenly as it arose. Such an outbreak is called a bourne, and is due to the saturation line being temporarily raised.

Ebbing and Flowing Springs and Wells near Seacoast. Where springs occur on the coast, their flow may be held up by the sea at high tide acting as a dam, and be only released at low tide.

Similarly, the level of water in wells near the coast may fluctuate with the tides.

Line of Saturation. Other conditions under which water occurs are illustrated in figs. 31 and 32. In fig. 31, A is an impermeable cap of clay, resting on a porous bed, B, which in its turn rests on an impermeable stratum, C. The water which falls on A will sink into the porous stratum, B, and accumulate nearly to the level of *a b*, at which level it is drained by springs, breaking out at *c*. In wells sunk at *e* and *f* the water will rise to the level of the line *a b*; also, in borings made at *d*, the water will probably rise through the borehole and overflow the surface, forming what is called an overflowing artesian well. It is evident, if the mass A covered the permeable strata to a higher level than *c*, namely, to as high a level as the edges of the bed C, then the line of saturation would correspond with that upper level—a distinction which will be sufficiently understood by inspection of fig. 31 without the aid of another diagram.

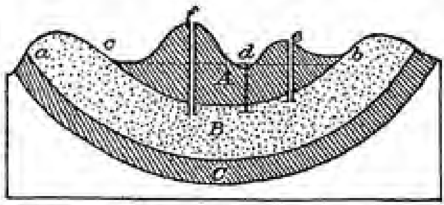

FIG. 31. Water at outcrop of permeable between two impermeable beds.

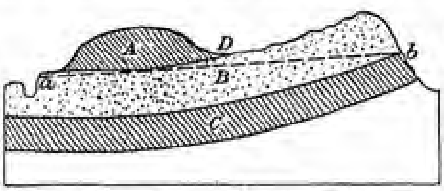

FIG. 32. Inclined line of saturation.

Fig. 32 represents the case of a basin drained by a river and having an inclined line of saturation. Here A, B, and C represent the same succession of strata as in fig. 31. At *a* is a river, where the water lodged in B finds the means of escape; and hence the line of saturation and the height to which water will rise in wells become the line *a b*, drawn from the outcrop of C to the mean level of water in the river at *a*.

It is evident, if any part of the surface of B should lie below *a b*, that we may expect to meet with springs breaking out on the surface; and so, if any part of the surface at A should lie below *a b*, then we may expect to find overflowing artesian wells, as in fig. 31.

It is probable that the line of saturation *a b* is not invariably a

straight line, but in dry seasons is depressed into a hollow curve beneath the straight line, while in wet seasons it swells into a convex curve above the straight line. If we conceive it to swell in wet seasons to such an extent as to cut the surface, D, at any point to the right of the mass, A, we shall have for a time a spring flowing at that point. This is one mode of accounting for intermittent springs.

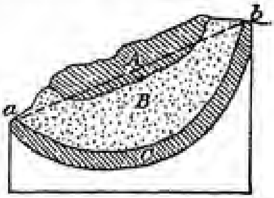

FIG. 33. Inclined line of saturation.

Fig. 33 shows an arrangement of strata which often prevails in nature, the impervious mass, C, cropping out at very different levels, *a* and *b*. Here the line of saturation also will be inclined from *b* to *a*, and at this level the water will stand in wells sunk between *a* and *b*.

Fault Springs. Fig. 34 is a section across a valley, B, looking up the same, in the neighbourhood of a fault. The hills A, C are supposed to be formed of a permeable stratum, *a a′ a″*, resting on an impermeable bed of clay, *b b′ b″*. Between these two hills is a valley of denudation, B, towards the head of which the junction of the permeable stratum *a a′* with the clay bed *b b′* produces a spring at the point S; here the intersection of these strata by the denudation of the valley affords a perennial issue to the rain-water which falls upon the adjacent upland plain, and, percolating downwards through the porous stratum *a a′*, accumulates therein until it is discharged by numerous springs in position similar to S, near the head and along the sides of the valleys.

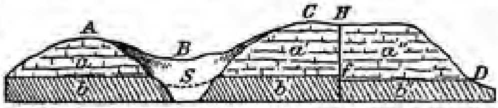

FIG. 34. Origin of two kinds of springs.

The hill C represents the case of a spring produced by a fault, H. The rain that falls upon this hill between H and D descends through the porous stratum *a″* to the subjacent beds of clay *b″*. The inclination of this bed directs its course towards the fault H, where its progress is intercepted by the dislocation edge of the clay bed *b′*, and a spring is formed at the point *f*. Springs originating in causes of this kind are of very frequent occurrence, and are easily recognised in cliffs upon the seashore.

Three such cases may be seen on the banks of the Severn, near Bristol, in small faults that traverse the low cliff of red marl and

lias on the north-east of the Aust passage. In inland districts the fractures which cause these springs are usually less apparent, and the issues of water often give to the geologist notice of faults of which the form of the surface affords no visible indication.

Figs. 35 and 36 show one of the most common modes of occurrence where the fault X has caused a dislocation of the strata and brought down the impermeable bed A in contact with the porous stratum B. Fig. 35 shows the spring breaking out in the valley at X; but the same effect sometimes takes place near the tops of hills or on high tableland, as at X, fig. 36, especially if the beds in B dip towards X.

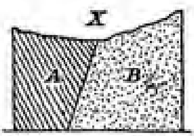

FIG. 35. Spring in valley caused by fault.

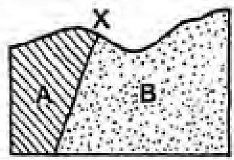

FIG. 36. Spring on hill caused by fault.

It has been observed by geologists that the occurrence of springs in limestone districts is one of the best indications of the existence of faults. In the Carboniferous district of Gower the limestone is traversed by a succession of nearly parallel faults, which range across the limestone at right angles to the coast-line. The lines of these faults are invariably marked on the surface by a series of springs breaking out at different levels from that of the sea, up almost to the summit of the country. The lower springs are far more copious, and some of those near the level of the sea never cease to flow, while those at the higher levels are readily affected in dry seasons, and often cease for months together to yield a drop of water.

Springs arising from faults, unlike those caused by alternation of strata in valleys of denudation, are by no means confined to combs or valleys. On the contrary, they often appear on tablelands and other high elevations. The great boundary fault of the Dudley coal-field, in the neighbourhood of Wolverhampton, where the magnesian limestone and Red Sandstone marls are brought down in contact with the Coal Measures, gives rise to numerous springs almost at the summit of an elevation district along the margin of the coal-field. Many of these springs burst up in an almost vertical direction, and may be seen in several cases breaking

through the hard surfaces of roads and flowing over into the gutters.

Dyke Springs. Springs are occasionally thrown out by dykes or thin layers of impermeable material intersecting a water-bearing stratum, as in fig. 37. The water will accumulate between the impermeable substratum and the dyke, until it makes its appearance on the surface at S.

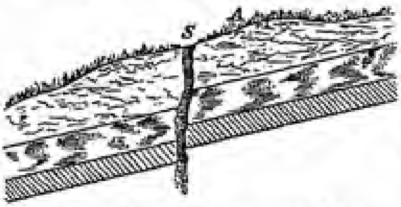

FIG. 37. Spring thrown out by a dyke.

Springs as a Source of Supply. Long-continued observation is the only safe guide for ascertaining the relationship which subsists between the flow of a spring and the rainfall upon the area from which water is drawn. Springs may more frequently be utilised as contributing to a supply than as the sole source. Sometimes, two or more springs, too small independently for the demand to be met, may be led into a common reservoir, serving also, perhaps, as a service or town reservoir. One advantage to be drawn from the joint utilisation of waters from different springs, is that probably their least separate discharges will not occur at precisely the same season of the year. Difference in the extent, nature, situation, elevation, and distance of their respective drainage grounds, and also difference in the lithological characters, massif,[1] and inclination of the respective strata, may bring this about, but always with the advantageous result that the periodical diminution of flow in any one spring will be more or less neutralised by the more liberal flow from the others.

WELLS

Wells are either shallow or deep, as explained below; they may also be divided into ordinary and artesian.

Shallow Wells. Wells which are sunk comparatively but a short distance into a superficial water-bearing stratum are known as shallow wells. They are supplied by the infiltration of rain and other water which falls on the adjacent surface of the ground, or which is drained from ponds, cesspools, sewers, rivers, or other

[1] A French term for a mountainous mass or group of connected heights, whether isolated or forming part of a larger mountainous system. A massif is more or less clearly marked off by valleys.

reservoirs and channels. The numerous wells sunk for domestic purposes in many villages and towns are, as a rule, of this kind. They are highly objectionable when situated in the immediate neighbourhood of towns, cemeteries, highly cultivated lands, and other sources of organic matters; but localities may frequently be discovered where the conditions are favourable for sinking them, and where at the same time the water will be wholesome and comparatively pure.

The *quantity derivable* by these means will depend upon the depth of the well, the nature and position of the water-bearing stratum in which the well is sunk, and the disposition of the impermeable stratum below. If the well be sunk in a permeable stratum, as in fig. 27, the water derived from it will be simply that which, in percolating downwards through the pores and fissures, flows in through the sides of the well, because of the diminished resistance to its passage, more quickly and from a larger surface than it can filter away through the bottom of the well. This *drip water* is an element in the yield of all shallow wells and of some deep ones. In the case of fig. 28, if the well is carried down below the line of saturation A B S, the supply will no longer be limited to the drip water, but will be drawn from the subterranean reservoir formed by the depression in the underlying impervious stratum. The distance from the ground surface to the line of saturation will sometimes vary considerably, even in closely adjacent sites. Irregularities or undulations of the retentive substratum may divide the geological basin into different reservoirs with different lines of saturation, and thus render the selection of the most favourable site a somewhat doubtful task. Shallow wells are frequently sunk in the vicinity of rivers and lakes, and are supplied by the water filtering through the sands, gravels, or rocky detritus which forms their margin.

Deep Wells. Wells which are supplied by water which has had to percolate and filter through large masses of the earth's crust are known as deep wells. The difference between shallow and deep wells consists rather in the greater or less distance of the source of the water which flows into it than in the actual depth of the well; for a deep well, or more properly a deep-seated well, may be formed by sinking through a moderately thin bed of clay or rock into a water-bearing stratum, whose nearest drainage area or outcrop is at a considerable distance.

Causes of Success or Failure. The conditions which affect the

success of a well, as far as the yield of water and its level are concerned, are so varied, that any attempt to illustrate them with an approach to completeness would be futile. The cases which are given here must be regarded only as a few types.

One of the most frequent causes of either success or failure is the existence of faults in the strata in which a well is sunk. Referring to fig. 37, let it be supposed that the fault there shown has been filled with an impervious material, forming a dyke which serves to retain the water in the permeable stratum lying above it. A well sunk, say, at A, in the latter would yield a supply more or less abundant according to the extent of the exposed surface of that part of the water-bearing stratum, while one sunk on the other or lower side of the fault would evidently be a failure, as far as the yield is concerned. If, however, the fault were filled with the detritus of the adjacent strata in such a manner as to freely admit the passage of the water, it is obvious that the most favourable site would be one below the fault, carefully selected with regard to the position of the fault on plan, and also in such a manner that the fault would be intersected by the well; for the water from a comparatively large extent of the stratum would be drained into the fault and thence into the well. Should the fault not be struck in the vertical line of the well, a tunnel or heading driven from the well into the fault would have a similar result.

Wells as a Source of Supply. The waters of 'shallow' wells are frequently unfit for human consumption. The waters of 'deep' wells will depend for their characteristics upon the nature of the strata through which they have percolated and the soluble matters contained therein; they are more free from organic matters than river-waters, as they undergo a more or less complete natural filtration; the greater the depth of the well, or rather the longer the time which the process occupies, the more complete will be the oxidation of the organic matters.

When comparing different sources on the ground of purity, note must be taken of the possibility of contamination at future periods, such as by mineral workings in mountain districts, or by the cultivation of the land, or the increase of population in the district. Of all sources, deep wells are least liable to have the quality of their water injured by such causes, because of the great depth of natural filtration which the waters undergo.

Artesian Springs and Wells. In fig. 38, A and C are beds of clay or other impervious material, and B is a water-bearing

stratum. Water will accumulate in the hollow of the lower impervious stratum until it is pressed upwards against the under side of the upper one by hydrostatic force. If, therefore, a well be sunk or a hole bored, say at K, the water will rise to a level determined by this hydrostatic pressure. Such wells are called artesian, from the French province of Artois, where they are very common, and were executed with the greatest success as far back as the twelfth century. If the upper surface of the impervious stratum be below the level determined by the hydrostatic force just mentioned, a borehole through the impervious stratum at that point will give rise to an overflowing artesian well. A natural fissure in the impermeable stratum will, under similar circumstances, give rise to an artesian spring. In fig. 39 these conditions are illustrated. The rise of the water from the borehole at A, or the spring at S, will be seen to depend on the elevation of the outcrop of the pervious stratum at B.

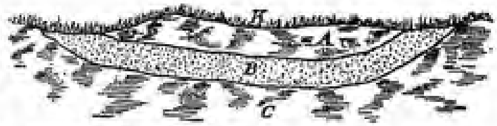

FIG. 38. Water held down in porous bed by superimposed impervious stratum.

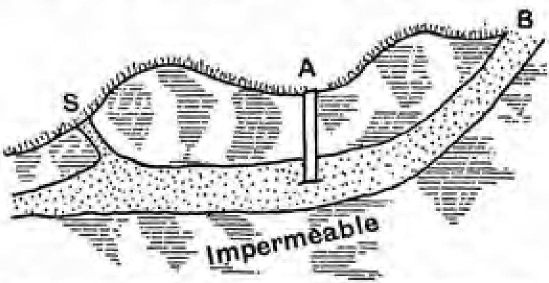

FIG. 39. Natural fissure giving rise to artesian well.

'The epithet "artesian" has been often indiscriminately applied to all deep wells formed by borings; but it is more correctly confined to those wells in which the water rises up with some force to the surface, and overflows, in consequence of the hydrostatic pressure of the water contained in the higher parts of a permeable stratum which the well has pierced. Wells, accordingly, to be really artesian, must be located in a valley, or on low-lying ground in relation to the surrounding district, so that the permeable

stratum, enclosed between two impervious beds, into which the boring is carried, may rise sufficiently on one or both sides above the surface level at the site of the well, before reaching its outcrop, for the hydrostatic pressure in the stratum to overcome the frictional resistance to the flow of the water through the stratum and up the well.

'The success of an artesian boring evidently depends upon the complete enclosure of the water-bearing stratum between impermeable beds underground, the height of the outcrop of the water-bearing stratum in relation to the level of the ground at the site of the well, and the perfect continuity of the stratum between its outcrop and the well.' [1]

Sub-artesian Wells. 'Often the elevation of the outcrop of the water-bearing stratum, though insufficient to make the water overflow from a well situated in low-lying ground, is, nevertheless, adequate to raise the water in the well considerably above the level at which the water was first met with in piercing the water-bearing stratum in a dip. Such a well is somewhat artesian in character, or "sub-artesian" as it has been termed; and the pumping required to raise the water to the surface is proportionately diminished. The discharge from artesian wells is frequently reduced, and sometimes ceases altogether to overflow, when other borings are sunk into the same stratum, bringing the wells down to the sub-artesian type of well just described. This result is due to the lowering of the general plane of saturation in the water-bearing stratum, and the consequent decrease in the hydrostatic pressure by the increased draught on the water; and it is most apparent when the new borings are carried lower down into the water-bearing stratum than the old ones, and when the extent of the outcrop of the stratum is relatively small.' [2]

Prospecting for Water

In addition to collecting all local information with regard to rainfall and the permanency of flow of springs, streams, and rivers, the engineer who is seeking for reliable springs or sites for wells must make a careful investigation of the geology of the district.

In Great Britain geological maps are available for most districts,

[1] L. F. Vernon-Harcourt: *Sanitary Engineering*, pp. 54–55.

[2] L. F. Vernon-Harcourt: *Ibid.*, pp. 56–57.

but even these must be supplemented by a detailed examination as explained in Chapter VI, seeing that local variations cannot be depicted on any small scale map. The lithological character of formations often varies considerably and water-bearing strata are frequently discontinuous. Where no map exists a complete geological survey must be made.

Having collected all necessary information and made sufficient traverses (see Chapter VI), geological sections should be prepared to show:

The nature of the rocks and their structure, including unconformity, overlap, inclination, and faults.

The thickness of strata and breadth of outcrop of water-bearing and other formations.

The nature of the superficial layer.

Water Divining. When prospecting for water the engineer will do well to call in the aid of a well-known water diviner, and collate the information thus obtained with the geological considerations as noted above.

There can be no doubt, in spite of the prejudice against this fact, that from mediæval times up to the present time water divining or *dowsing* has been successfully used to find water. The late Sir William Barrett, whose investigations are recorded by Mr Theodore Besterman in *The Divining Rod*, published in 1926, in a letter to *The Times* in 1905 stated that 'making a liberal allowance for failures of which I have not heard, I have no hesitation in saying that where fissure water exists and the discovery of underground water sufficient for a domestic supply is a matter of the utmost difficulty, the chances of success with a good dowser far exceed mere lucky hits, or the success obtained by the most skilled observer, even with full knowledge of the local geology.'

Many instances of successful dowsing are given in *The Divining Rod*—notably at Waterford in or about 1888—and in a smaller book, *Water Divining*, by Theodore Besterman, published in 1938, and the evidence in favour of successful dowsing continues to accumulate.

On the question as to *how it is done*, many and diverse theories have been put forward, but whatever may turn out to be the cause of the dowsing faculty, the engineer may content himself with the knowledge that water diviners have been employed or recommended to be employed by at least five County Councils, seven Urban District Councils, and forty-two Rural District Councils

within the last few years in the United Kingdom, and that water diviners are much employed abroad.

SECTION IV. RIVERS

Flow of Water. 'Rivers are channels that maintain a perennial though ever-varying discharge. The formation of a river is due to precisely the same cause as that of the smallest rill. It owes its maintenance to the rainfall of its district preserving the level of the surface of saturation above the natural hollow that forms its bed. The occurrence of river-valleys, small originally, but ever widening and deepening by the erosion due to the scour and fretting of their currents (see Chapter I), offers to the water percolating through adjacent land a course of less resistance than that of the interior of the rocks; the subterranean waters gravitate towards the bottom of the valley; the surface of saturation is depressed in the vicinity, rapidly at first, but flattening as the river is approached (see fig. 40), and emerges from the ground coincident with the hydraulic surface of the river. The water flowing in rivers is contributed in three ways: directly, by adventitious surface flow and by rain; indirectly, by rivulets and ditches, which tributaries derive their own flow as miniature rivers; and, normally, by the percolating land-water that enters their beds under the hydraulic head of the neighbouring subterranean waters. The last-mentioned form of contribution is sometimes peculiarly marked by the evident increase in the size of rivers, without the apparent cause that is afforded by the junction of the tributaries. Thus, in defining the watershed or catchment area of a river, it is necessary to consider not only the superficial extent of land that discharges surface-water into it, but, further, the area from which underground water is contributed to it—two elements that are seldom coincident.'[1]

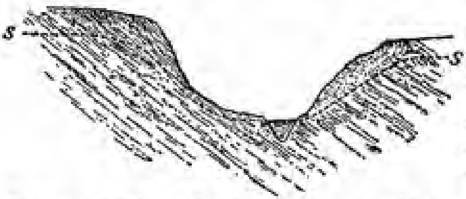

FIG. 40. Surface of saturation near a river.

Fluctuations in flow are referred to more fully in Chapter XII, Section I.

Quality of Water Dependent upon Strata. The water found in

[1] Tudsbery and Brightmore: *The Principles of Waterworks Engineering*, 3rd ed., pp. 19–20.

rivers, streams, and lakes is that which has been immediately drained into them from the surface of the land or that which having been previously absorbed by porous strata, has fed them in the shape of springs; or, that which has been drained into them by artificial means. In any case, however, the nature of the foreign matter contained in river-water will depend upon the nature of the strata through which it has percolated and over which it has flowed.

Where the rain falls on impervious strata, such as *granite*, it runs off the surface without encountering any substances which it can dissolve to any great extent; it therefore remains comparatively free from foreign matters. The water from rivers and lakes in such districts approaches more nearly the nature of rain than any other natural water. It is the softest of river-water, and its solvent powers are therefore comparatively high.

The next waters are the rivers which have passed over or through districts containing *carbonate of lime* in some form or other. They vary but little in the nature of their inorganic constituents (consisting principally of carbonate of lime, sulphate of lime, carbonate of magnesia, and chloride of sodium), but vary very considerably in the total quantities of these substances, and the proportions of them one to the other in the several waters.

Much has been said in favour of a supply from large rivers on sanitary grounds. The water is usually softer than that derived from wells, springs, and small streams, and contains a less amount of mineral salts than either of these, at the same time that it is commonly more impregnated with organic matter. A large river flowing over many geological formations and many different varieties of soils may naturally be expected to take up in solution a variety of mineral matters, and therefore to present a greater number of ingredients than water derived from a more limited area; and this is generally found to be the peculiar character of river-water.

It must be remembered, however, that rivers which drain large areas of cultivated land, and into which the sewage of towns on their banks must sooner or later, and in either a crude or modified form, find its way, are always open to suspicion.

The *self-purification* of streams during their flow has engaged much attention; and, although it must be conceded that such action does take place, it is infinitely less effective than the natural processes of filtration and distillation. Further information with regard to this subject must be sought elsewhere.

River Schemes. In these, water is drawn from a stream or river whose flow is greatly in excess of the quantity to be abstracted. This excess makes one of the chief differences between river schemes and impounding or gravitation schemes; inasmuch as, in the latter, storage reservoirs, to equalise the supply and demand, are essential, whereas in the former, reservoirs for such purposes are, except in very rare cases, quite unnecessary. It is sufficient that the smallest dry-weather flow of the river is so large as not to be injuriously affected by the withdrawal of the quantity required for the works.

The great experience and careful observation necessary for the success of large gravitation works may be here largely dispensed with—that is, as far as ensuring an abundant supply is concerned. The larger the stream, the smaller, proportionately, will be the variation in its flow at different seasons. The greater extent of the drainage area will alone be a moderator of the effects of irregularities in rainfall; and even more so will be the existence in that drainage area of absorbent strata serving to retain the rain-water only to yield it again in the form of perennial springs. And thus it is that droughts which would threaten the complete failure of impounding works need scarcely be regarded in connection with river schemes.

Flow of Streams and Rivers. 'The discharge of watercourses, which constitutes the available rainfall of the basins which they drain, with the exception of any springs flowing straight into the sea, or any water which may be drawn off from underground sources, varies with the conditions which, as already pointed out, affect the flow of the rainfall off the ground. The strata forming the upper portion of the basins of rivers on high ground are generally impermeable, the fall of the upper river is large, and the rainfall greater than on the lower ground. Accordingly, the flow of streams draining the higher portions of river basins is usually very irregular, the streams rising rapidly in high flood during rainy weather, and running almost dry in dry weather. In the lower part of a river basin, on the contrary, the ground is commonly somewhat alluvial, and therefore permeable, the fall of the river is reduced, and the discharge, being derived from a much larger area, is much more uniform, and less liable to sudden variations from great fluctuations in rainfall usually limited in extent. Rivers, consequently, in the lower part of their course, besides having necessarily a much larger discharge, possess a more regular flow; and even in tropical countries, the main rivers draining large basins subject to varied

meteorological conditions still maintain a discharge in the dry season. Moreover, sometimes rivers rising in mountainous districts with a large rainfall, eventually in their course to the sea traverse almost rainless districts, bringing water to these arid tracts, which would be uninhabitable without them, of which the Nile and the Indus furnish typical instances.'[1]

Rivers, however, do not necessarily have a larger discharge in the lower parts of their course, *e.g.* the Nile, where enormous quantities of water are lost in the Sudd regions (see Sir W. Willcock's *Report on Assuan Dam and Egypt Fifty Years Hence*). Again, sometimes rivers disappear underground, or a large portion of the discharge will flow underground to appear above ground again farther down. Some rivers of considerable volume in hilly country dry up and disappear altogether in the sandy deserts lying at the foot of the hills.

The following particulars of the summer discharge of rivers, taken from Mr Beardmore's *Annual*, are of value in connection with this subject, as showing the powerful influence of retentiveness in the geological character of the drainage ground acting even in opposition to the moderating effect of extent:—

TABLE III. SUMMER DISCHARGE OF RIVERS

Rivers	Drainage Area	Summer Discharge				Mean Annual Rain-fall
		Total	Per sq. mile	Per 1000 acres	Equiv. Annual Rain-fall	
	Sq. miles	Cu. ft. per min.	Cu. ft./min.	Cu. ft./sec.	Inches	Inches
Nene, at Peterboro': oolites, Oxford clay, and Lias .	620	5,000	8·45	·22	1·88	23·1
Thames, at Staines: chalk, greensand, Oxford clay, oolites, etc.	3086	40,000	12·98	·338	2·93	24·5
Loddon: greensand	222	3,000	13·53	·352	3·01	25·4
Mimram: chalk .	50	1,200	24·0	·625	5·5	26·6
Wandle: chalk .	41	1,800	43·9	1·147	9·93	24·0

The larger percentage of summer discharge in the case of the chalk rivers may be explained as follows. Rivers flowing in a clay

[1] L. F. Vernon-Harcourt: *Sanitary Engineering*, p. 24.

basin are only fed by the rain falling within the actual basin; and as this rain evaporates very slowly in winter and very rapidly in summer, such rivers are subject to great winter floods and to severe summer droughts. The flow in chalk districts is, however, much more uniform, because the rivers are fed by springs as well as by surface drainage; hence the water stored up in the subterranean reservoirs is discharged by chalk rivers even in the driest seasons. In fact, they draw their supplies from areas beyond their actual basin, and their discharge is much more uniform throughout the year than in most other rivers.

SECTION V. LAKES AND IMPOUNDING RESERVOIRS

Comparative Advantages. 'The purest supplies of water are obtained from lakes in hilly districts, and from impounding reservoirs formed by dams enclosing the valleys of mountain streams, especially where the lands draining into them are devoid of habitations and culture. Moreover, the rainfall in mountainous districts is, under ordinary conditions, considerably greater than on lower ground; and as the hills are commonly formed of impermeable strata, and the slopes of their sides are steep, a large proportion of the rainfall flows down them into the valley below. Accordingly, with a large available rainfall out of a considerable total fall, the flow of a given drainage area is much greater in such regions than elsewhere; whilst the loss from evaporation, both over the land and the reservoir, is reduced by the comparative coldness of high altitudes. The catchment basins of mountain streams are, indeed, necessarily very much smaller than those of rivers in the lower portion of their course; but lakes converted into reservoirs for water-supply, and artificial impounding reservoirs, possess the very important advantage of storing up the surplus flow in flood-time for use during dry weather. These reservoirs of water, moreover, when situated in high, mountainous country, enjoy the further merits of being free from sources of pollution, and of being at a sufficient elevation above the district to be supplied, for the water to be conveyed by gravitation to the service reservoirs.'[1]

[1] L. F. Vernon-Harcourt: *Sanitary Engineering*, p. 81.

Drainage Areas

The **source of supply** in gravitation works is the rainfall upon the gathering ground or catchment basin, a tract of land more or less completely bounded by ridge lines, or more properly watershed lines. This latter distinction is necessary, because the hydrographical basin is not necessarily coincident with that traced from surface contours. Valleys of denudation on an anticlinal axis, for instance, where permeable strata are superimposed, would show from surface contours a gathering ground larger than the drainage area really available for the impounding of water, and *vice versa*. In impervious or rocky districts the case is simplified to one of surface observations.

Size of Catchment Area. 'Unusually heavy falls of rain are the determining causes of the excessive floods that occur on catchment areas; and, as might be supposed, the relative magnitude of such floods is greater in the smaller areas.

'There are two reasons for the decrease of the rate of flood discharge as the catchment area increases: (1) Extremely heavy falls only last for a short time, and rain falling in the remote portions of a large watershed takes appreciably longer to flow to the place of discharge than does the rain precipitated at more central parts; so the duration of the flood is prolonged, whilst its intensity is diminished. (2) Heavy falls of rain, occurring only locally over limited areas, naturally affect but slightly the discharge from extensive watersheds.

'It is useful to remember that 1 inch of rainfall per twenty-four hours over 1000 acres is approximately equivalent to 42 cubic feet per second. Also that a fall at the rate of 1 inch per hour corresponds with a discharge of 1 cubic foot per second of an area of 1 statute acre.'[1]

Determination of Yield from Catchment Area. To arrive at the available yield from a catchment area the following points should be considered:—

(1) The available rainfall.
(2) The quantity of rainfall lost by evaporation and absorption by vegetation.
(3) The geological structure.

[1] Tudsbery and Brightmore: *The Principles of Waterworks Engineering*, 3rd ed., pp. 40–41.

(4) The amount of percolation into and out of the area.

(5) The maximum period during which the available supply falls short of the demand.

Available Rainfall. The gathering ground having been determined, and its area ascertained, an estimate has to be made of the available rainfall upon that area.

The available fall is a quantity more or less short of the mean fall—how much so remains to be seen. The mean annual fall is referred to in Section I, and the first deduction from this is one rendered necessary by the variations in the amount of fall. The extent of the variations, as already stated, is found to be about two-thirds of the mean fall—that is, one-third in excess and one-third in defect. Were the whole of the rainfall (neglecting for a moment the loss by evaporation) to be impounded, and a uniform quantity, equal to the mean fall, to be discharged from the reservoir, the storage capacity of the reservoir would have to be far greater in proportion to the supply than has hitherto been found economical. The greater the mean supply (rainfall) compared with the mean demand, the less will be the storage capacity required to ensure the demand being regularly met ; and it is now the practice to consider as available no more than the mean fall for three consecutive dry years, and to secure a gathering ground correspondingly large. Where an extension of catchment area presents difficulties, and an increase of storage capacity unusual facilities, a modification of this practice may be advantageous. The mean fall in three consecutive dry years is found to be, with remarkable regularity, one-sixth less than the mean fall, and this deduction is therefore always made ; the one-sixth passes away in floods which the reservoir is not large enough to impound.

The next deduction is for the loss by evaporation and absorption, which varies in this country from about 9 to 19 inches per annum (*vide* Section I) ; an estimate of it for any case can be formed only from careful observation and experienced judgment. The actual loss for a particular period may be found by comparing the gaugings of the stream or stream's bed from the drainage ground with the returns from the rain-gauges for the same period. The difference will, of course, give the loss for that period. If the period of stream-gauging be one in which the rainfall has proved to be less than the mean annual fall, the proportionate loss shown by the gaugings will be greater than the proportionate mean loss, and

vice versa. Gaugings for short periods require to be treated with the greatest caution, and in inexperienced hands would be almost sure to lead to erroneous conclusions.

Ratio of Runoff from a Catchment Area to Total Rainfall on the Catchment. A table of the proportion of rainfall running off into outfalls, from observations at Nagpur by A. Binnie, is given in Molesworth's *Pocket Book*, 27th ed., p. 319. Captain A. ff. Garrett, R.E., states that he has tested these in the Central Provinces, India, and found them remarkably correct—generally within 5 per cent. Probably similar percentages would hold in other parts of the world. In Rajputana, he says, they generally took for new projects 10 per cent. run-off from sandy catchments and 20 per cent. from hilly ones, though in exceptional cases as much as 70 per cent. has been obtained off bare rocky catchments. It is, however, almost impossible to make an accurate estimate unless there are previous records to go on.

In the case of the **Tendula** project, in the Central Provinces, for a storage tank to impound 18 square miles of water, Captain Garrett worked out the probable supply as follows:—

Catchment area is over 300 sq. miles in two valleys. Rain-gauges were established in the centre of each valley and read for two years and compared with readings from the gauge at Dhamtari, some 30 miles distant, of which there were records for thirty years. By taking proportions, the mean rainfall of the Tendula catchment for past thirty years was then worked out, taking the Dhamtari records as basis. At the same time the Tendula river was carefully gauged daily for two years—the gauges being read every four hours during high floods. From the results of these gaugings the percentage of run-off was calculated and a curve was plotted showing the percentage run-off after 20, 25, 30, 35, 40 inches of rain had fallen. From this curve the yield for each of the thirty years was then deduced from the calculated mean Tendula rainfall. Again, from the rainfall statistics it was possible to estimate when water would have been required for irrigation. Allowing for water drawn off for irrigation, and 5 feet loss annually for evaporation and absorption, it was possible to completely trace the working of the whole scheme, supposing it had been in existence for thirty years, and thus to form a very fairly reliable forecast of its working in the future.

Loss by Evaporation. 'The portion of the rainfall which finds its way into the streams or springs draining a catchment area that

is but slightly permeable depends largely upon the activity and extent of evaporation and the absorption of water by plant life. The subject of evaporation has already been alluded to (*vide* Section I); its effect is naturally more marked in flat than in hilly districts from which water rapidly flows away, and is in a peculiar degree dependent upon the distribution of rainfall throughout the year. In valleys with steep hills on each side, subject to a heavy rainfall, the loss from evaporation in this country during the winter is insignificant. In dry districts it frequently happens that during the summer months nearly the whole of the rainfall disappears.' [1]

The **geological structure** is extremely important in estimating the capacity of a drainage area. It is not alone the rain which falls on the sloping surface of the hills and finds its way by gravitation to the lower levels, but the effect of springs is also often very great in augmenting the quantity of water. Mr Beardmore relates an instance where an oolitic district was found discharging a very large quantity of water with scarcely any drainage area lying above or beyond it. In this case the porous strata, with a very small dip cropping out on the sides of the valley, were delivering the water which filtered into them far beyond the limits of the drainage area, as indicated by the levels of the surface. In fact, many districts will be found to have a geological drainage area as well as a surface drainage; and it often happens that the former is far the most important of the two.

The geological maps of the Ordnance Survey will be useful in studying the geological structure, but as these maps only show the underlying rocks and do not give sufficient information as to the surface when covered with drift, gravel, etc., the methods of observation alluded to in Chapter VI, Section I, should be followed.

Percolation necessarily depends on the geological structure. It is not only the percolation *out* of the catchment area which has to be taken into account, but the possible percolation *into* the area.

Percolation out of the area may be due to fissures in rock in the valley bed above the point where a natural or artificial reservoir is or has to be formed; or to pervious strata dipping outwards on one or other sides of the valley. Various projects in India and elsewhere have been spoilt owing to a rocky bed having been considered to be watertight, when there was actually hidden leakage due to fissures.

[1] Tudsbery and Brightmore: *The Principles of Waterworks Engineering*, 3rd ed., p. 49.

If on one side of the main valley of the catchment area there is a permeable layer dipping away from the valley, this layer will carry off much of the rain falling on its outcrop.

Similarly, if there is a permeable layer on the other side of the valley which dips towards the valley, it will bring into the valley rain-water falling on its outcrop on the reverse side of the hill or slope containing the valley.

In all cases where the surface is more or less porous (as much of it will be in any average catchment area), some part of the water will sink in to a considerable depth, especially in districts where there is much limestone, chalk-beds or sands, etc., and whether this water will again come to the surface in the catchment area depends on the underlying permeable and impermeable strata.

Percolation also depends on the *slope of the ground*, which also affects the loss by evaporation, for on steep slopes the water will run off quickly and percolation be less than on flatter ground.

Likewise the *rate of flow* of rainfall affects the percolation—less being absorbed when the flow is rapid than when it is slow.

Lakes

'**Natural reservoirs** are provided by lakes, formed generally by a depression in a mountain valley through which a river flows, in which the water is retained by a ridge of rock across the valley at its lower end, and over which it has to rise before the river flowing in at the upper end can continue its course down the valley below. The lake, in regulating the flow, stores up to some extent over its large area the flood discharge of the river above; and it also acts as an immense settling basin, in which all the sediment brought down by the river is gradually deposited as the current is checked on entering the lake. A notable example of this result is furnished by the River Rhone, which enters the Lake of Geneva as a very muddy, glacier-fed river, and emerges at Geneva as pure and blue as the waters of the lake. The value of lakes as storage reservoirs depends upon the discharge of the river flowing into them together with the flow of their own gathering-ground, and the freedom of the drainage area and the shores of the lake from sources of pollution.' [1]

Advantages. 'Lakes, by their very existence, prove that the strata forming their basin are thoroughly watertight, which is an essential condition in a reservoir. Another advantage possessed by

[1] L. F. Vernon Harcourt: *Sanitary Engineering*, p. 35.

lakes for conversion into reservoirs is the existence of a rocky barrier across their outlet, which is a cause of their existence; for the water discharged from them would have worn away any soft obstruction.' [1]

Impounding Reservoirs

Sites. The suitability of a site for an impounding reservoir depends on (*a*) the elevation being sufficient; (*b*) the catchment area being suitable and sufficient; (*c*) the capacity being satisfactory; and (*d*) the geological features of the site as a whole, including the area to be covered and the site for a dam.

Elevation. 'In the selection of sites, the engineer naturally chooses positions which, whilst sufficiently elevated to ensure the gravitation of the water to the district to be supplied, and a proper pressure throughout the entire system of distributing pipes, appear to lend themselves to the impounding of the required volume of water with the greater facility and economy of construction.' [2]

Catchment Area. See above under 'Drainage Areas.'

Capacity. 'In order that a storage reservoir may ensure the provision of a definite daily supply, its capacity must be sufficient for it to be able to continue supplying the requisite daily volume throughout the longest period during which there may not be enough rain over the drainage area for the reservoir to be appreciably replenished. The daily volume required to be furnished must, in addition to the water-supply, include the compensation water and loss from evaporation; and this volume, multiplied by the number of consecutive days during which practically no flow off the gathering ground may reach the reservoir, gives the required capacity of the reservoir for storage. This period of drought varies with the locality, being much shorter in very rainy districts, and over extensive drainage areas, than in dry places with limited gathering grounds, where the variations from the mean rainfall are greater; and the longest droughts occur in those tropical regions where the periodical rains are very irregular, failing sometimes to a great extent during the rainy season, and occasionally in some parts during two rainy seasons in succession.' [3]

Geological Features. 'Simultaneously with the favourableness of

[1] L. F. Vernon-Harcourt: *Sanitary Engineering*, pp. 81–82.

[2] Tudsbery and Brightmore: *The Principles of Waterworks Engineering*, 3rd ed., p. 180.

[3] L. F. Vernon-Harcourt: *Sanitary Engineering*, pp. 91–92.

the site for capacity, and for the formation of the bank in point of dimensions, the geological features must be carefully regarded, in order that a watertight reservoir may be constructed. The valleys of mountain streams draining uninhabited and uncultivated districts afford the most favourable sites for impounding reservoirs, owing to their freedom from pollution, and because, from their situation, they are exposed to a heavy rainfall, a large proportion of which, falling on very sloping impermeable strata, finds its way into the watercourse draining the valley.'[1]

The most suitable *site* is on rock, in a narrow gorge at the end of a fairly wide and flat valley, which is not liable to pollution and can be easily closed by a dam.

In many parts of the world valleys are formed by the erosion of anticlinal folds. These are undesirable as reservoir sites if any of the rocks forming the sides of the valley are porous; for, dipping away from the sides of the valley, as they must do, owing to the geological formation, leakage through the porous strata will be very difficult to prevent.

The *area to be covered by the reservoir* must be adequately impermeable and continuous throughout so as to be perfectly watertight, or capable of being readily made impervious in small defective places by layers of clay puddle.

If any porous strata be intersected it will be necessary to study their dip, for if it be away from the valley, such strata will only drain the reservoir of its contents; but if the valley be on a synclinal axis, the porous strata, if any, dipping towards the reservoir will, on the other hand, serve to augment its waters by the inflow of springs which most likely will be perennial. Cracks and fissures in rocks are frequently sources of leakage from reservoirs, and special means should be taken to stop all such as are discovered, by the introduction of concrete and puddle. The reservoirs of the Manchester Waterworks, situated on the Lower Coal Measures and the Millstone Grit, presented many difficulties in this respect. The mountain limestone also is full of fissures, by which the water is almost sure to be drained away. Where excavations are conducted in the interior of a reservoir, care must be taken not to cut through a sound watertight bottom, and expose a pervious stratum into which the impounded water may escape.

The best material for the bed of a reservoir is hard unfissured rock or compact clay. Limestone is unsuitable owing to tendency

[1] L. F. Vernon-Harcourt: *Sanitary Engineering*, p. 81.

to fissures, and because it imparts hardness to the water, and gravel is, of course, highly objectionable. But either of these are suitable if covered with a layer of compact clay which is continuous and watertight, and covers the whole area without a break.

The Dam. A narrow part of the valley should, if possible, be selected for the dam, so as to reduce its length, and a site where the valley widens out considerably above the gorge for some distance so as to provide an extensive area for the reservoir.

Suitable sites for dams are often found just below the junction of two or more streams, as in such cases two or more valleys are available as storage basins.

It is also most important in selecting sites for storage reservoirs to see that a suitable position for the waste weir is available, so that floods may be discharged harmlessly.

It is very necessary to see that the banks supporting the dam show no tendency to landslips. The strike of the rocks in the valley is also important, the best site for a dam being where the strike of the rocks is parallel to the length of the dam. Again, where the dips of the rocks are upstream, sites for dams are preferable to where the dips are downstream.

Trial Pits. When the site of the dam has been provisionally selected, trial pits should be sunk at fairly close intervals along the proposed centre line of the puddle trench. These trial pits should be wide enough to expose a sufficient area to enable the strata to be carefully examined as to their suitability for the purpose intended.

SECTION VI. QUALITY OF WATER

Impurities

Absolutely pure water is not to be obtained in Nature; and fortunately it is not essential nor even desirable for the purposes of animal and vegetable life.

Rain-water usually contains ammonia, and in or near towns is always tainted with various impurities, chiefly due to smoke from household fires and manufactories.

Spring and Well-water contain numerous mineral substances, chiefly salts and gases, of great variety. The quality of such water is much affected by the rocks through which it passes, and water obtained from surface deposits usually contains some organic matter. The salts of soda, potash, magnesia, etc., will also be taken up, as well as sulphuric acid from decomposition. The

actual quantity of saline and other ingredients will, however, be less in amount in deep than in shallow wells.

River-water contains, in addition to the various substances obtained from springs and from rocks over which the stream passes, a quantity of organic matter, both of animal and vegetable origin, which in the neighbourhood of towns may include some sewage matter. The decomposing matter is, however, rapidly removed, partly by aeration and partly by bacteriological action.

Purest Water. Spring water is generally the purest as far as regards admixture with organic matter; but on the whole, and for most economic purposes, the best water is that obtained from mountainous or hilly districts, where there is abundant rainfall, and where the rain is collected on a surface of hard rock containing little limestone and no other soluble mineral.

Potability of Water

The potability or suitability for drinking purposes of water is dependent on:

(1) Bacteriological purity.
(2) Physical purity.
(3) Chemical purity.

Bacteriological Purity. While the freedom of drinking-water from forms of bacteria known to produce disease is of more importance than any other characteristic, the best method of obtaining such freedom is largely outside the province of the engineer, who must rely on the sanitary expert for advice on this subject. Bacteriological impurity can, however, be largely avoided by care in selection of catchment areas and sites of reservoirs.

It is eminently desirable that, when rain falls after a considerable period of drought, the first run-off should be diverted from the reservoir; but when this course is impracticable entire reliance must be placed on filtration, and in the selection of media for filtration either for filter beds or for mechanical filter plants, the engineer who knows something of geology should be able to assist the sanitary expert.

Physical Purity. Under this head come taste, odour, colour, and turbidity.

Taste and *Odour*. These are uncertain indications of the quality of the water from a hygienic point of view. Waters foully polluted

with organic matters are often so palatable that they have been preferred by the public to much purer waters. Any badly tasting or smelling water should be rejected or purified before use. Suspended animal organic matter often gives a peculiar taste, so also vegetable matter in stagnant waters. Some growing plants such as Lemma and Pistia give a bitter taste; but most growing plants have no taste. Dissolved animal matter is frequently quite tasteless. As regards dissolved mineral matters, taste is of little use and differs much in different persons. Iron when present to the extent of one-fifth of a grain to the gallon, and salt to the extent of seventy-five grains to the gallon, are detectable by taste.

The test of odour is unreliable, and odour may be evident in waters which are considerably polluted by sewage.

Many odours are due to the growth of minute organisms, specially of algæ.

A distinctly putrid odour is characteristic of large quantities of decomposing animal and vegetable matter, and a urinous odour is sometimes perceptible when large quantities of fresh sewage have gained access to water. The rotten-egg odour of sulphuretted hydrogen and that of coal-gas is distinctive. The presence of any of these last-named odours would condemn the waters, except in the case of waters naturally charged with the sulphuretted hydrogen and free from animal pollution.

Crenothrix, a fungoid growth, has occasionally given rise to disagreeable odour and taste in water supplied.

As a means of destroying algæ, confervoid, and other vegetable growths in water in which they are producing a bad taste and smell, the addition of copper or chlorine is of considerable value. Many American observers report favourably on the use of copper in this respect.

Colour. Perfectly pure water has a bluish tint, but many good waters have either a greenish-yellow or brown appearance. The best waters are those coloured bluish or greyish. Green waters owe their colour to vegetable matter, chiefly unicellular algæ, and are usually harmless. A yellow or brown colour is often due to animal organic matter, chiefly sewage. It is sometimes, however, owing to vegetable matter, such as peat, and in these circumstances is not generally harmful. It may also be caused, as is mentioned later, by salts of iron, although in most cases the iron is precipitated as ferric oxide in the sediment.

Many first-class water supplies, therefore, are highly coloured.

This yellowish colour originates for the most part in vegetable extractions, and where stains are usually prominent. Such colour has no hygienic significance, but offends the æsthetic sense of sight, and it has become the custom in large cities to use every reasonable effort to effect its removal before the water is delivered into the mains. Bacterial decomposition of the deposits on the bottom of some lakes deprives the lower strata of their oxygen, and such layers become highly coloured. With the periodic appearance of the 'overturn' in spring and autumn these coloured layers are brought to the surface, distributing the colour throughout the entire body of water.

Furthermore, under the anaerobic conditions sometimes existing at the bottom of lakes and ponds, iron is thrown into solution. On being brought into contact with air this iron is oxidised, imparting to the water a reddish-brown colour. Under ordinary circumstances sun-bleaching is actively felt for a depth of about one foot below the surface, and in a month's exposure to the sun's rays the colour removal will amount to about 20 per cent.

By treating coloured water with chemicals all vegetable stains can be removed. Ozonisation and the use of oxygenated compounds of calcium, sodium, or chlorine will effectively decolorise water, but their high cost is usually prohibitive were there no other objections to these forms of treatment. Filtrations of coloured water through clean quartz-sand will not effect measurable decolorisation, and it is well known that without the aid of a coagulating chemical, slow sand filters will not consistently remove more than about 20 per cent. of the dissolved colour in water. The most efficient and satisfactory method of water decolorisation is by coagulation, followed by filtration.

Turbidity. The ordinary citizen does not look with favour on a water which is turbid; that is, carries in suspension mud, silt, and clay in quantities sufficient to impart to it a marked cloudiness or a distinct muddy appearance. It is not so much a case of whether such matter is actually injurious, as that the water is not agreeable to the sight, and promotes other æsthetic prejudices such as those against taking into the system so much actual mud and dirt; and in fact even though the water is pure in other respects, the mechanical irritation of the human intestine by these suspended solids may cause diarrhœa and so predispose to more serious intestinal diseases. Therefore in all up-to-date cities where the water-supply is turbid, it is the custom to treat it in some way

before delivering it into the mains, in the endeavour to remove the turbidity and make it agreeable to the sight.

Effect on Health. What effect on the health of the consumer have these physical features as applied to water? A water heavily charged with mud will naturally possess an argillaceous or clayey taste and odour, the same being intensified by heating. This is not agreeable to many. Assume that a water contains on the average 100 parts per million of suspended matter. In a year's time an adult will consume in this way about ¼ lb. of such matter, or some 5 lb. in a lifetime. This quantity in itself cannot be considered as having any sanitary significance.

Water which is naturally highly coloured sometimes possesses a slight astringent taste; but such colouring matters, being vegetable stains for the most part, can have no deleterious effect on the health of the consumer. Some waters possess offensive tastes and odours, due to growths in them of certain higher forms of microscopical life, and due to the liberation by them of essential oils in process of their development or decay. These are relatively small in quantity, and cannot in themselves actually cause serious disturbances in the body of the consumer.

Finally, then, those physical characteristics natural to many surface-waters which lend to them an unsightly appearance, or an objectionable taste and smell, are of actual injury in so far as they may affect the individual imaginatively. This feature is not to be disregarded, however, for there is no doubt that many thousands of people actually have thought themselves into the grave. One of the first lines of common-sense water logic, therefore, is that drinking-water shall be free from perceptible quantities of colour and turbidity, and that it shall possess no disagreeable or actually foreign tastes or odours.

Chemical Purity. Under this head come hardness, iron, organic matter, chlorine, carbonic acid.

Hardness. Water, in its passage over and through the soil, dissolves and picks up certain minerals, among the most common being lime and magnesium. These give to the water its hardness. There are two kinds of hardness, namely, temporary and permanent. The carbonates of lime and magnesium, held in solution by the dissolved carbonic acid in the water, together with some sulphates of calcium (magnesium) and, if present, salts of silica, alumina, and iron, constitute the temporary hardness and may be almost completely softened by boiling. Waters which,

in addition to dissolved carbonates, contain in solution certain other sulphates together with chlorides, nitrates, and phosphates of calcium and magnesium, and some iron or alumina, cannot be effectively softened by boiling. Such hardness is termed permanent.

Hardness determinations are highly important, and should be carried out as routine in all waterworks laboratories. By determining the total hardness and the alkalinity (the difference generally representing the permanent hardness), records are obtained which are of value in settling discussions as to the advisability of softening the water; in soap consumption, on its utility for various industrial purposes, and on its suitability for steam raising. Where a coagulating chemical is used in the purification of a water-supply it is indispensable, owing to the fact that a certain amount of alkalinity is required to decompose every grain of added coagulant; otherwise, if the alkalinity be deficient, coagulation will be unsatisfactory and undecomposed coagulant will appear in the treated water—an inadmissible condition.

It is the contention of some physiologists that those constituents which make water hard are deleterious to the public health. In some cases this view would seem to have considerable merit. The traveller is unpleasantly reminded of abruptly changing from a soft to a hard water, and *vice versa*, but there are no statistical data to prove that in general the hardness of a water has any clearly defined effect one way or the other on the public health. Although it is strongly maintained by some that various specific diseases, such as urinary calculi, goitre, etc., are produced by the continued use of very hard waters, confirmatory data to prove the correctness of this view are lacking. It is much more probable that the action of hard waters is really restricted to simple gastric and intestinal disturbances, which are temporary only in their effect.

Iron. Practically all natural waters contain iron. The soil contains iron in the form of sulphide or oxide. Being dissolved out in water it may be present as an oxide, a carbonate, or as 'humic acid,' the original organic compound which holds ferric oxide in solution. Ferric oxide can be removed by sedimentation and filtration; ferrous carbonate by aeration through the opportunity thus afforded for the escape of carbonic acid, and, if the iron happens to be in combination with organic acids, the addition of alkalies will break up the loose combination and liberate the iron. Generally speaking, no water can be considered entirely satisfactory which contains more than about one part of total iron per million

parts of water. Even a less quantity than this is desirable, as a taste is sometimes perceptible in water containing about one part of iron.

The chief objections to iron in a water-supply from a sanitary standpoint are its undesirable taste and appearance when present in sufficiently large quantities. When it comes from the source of supply, it can readily be removed by aeration and filtration; and when it comes from the service pipes, through the corrosive action of carbonic acid or other agents, corrective measures have to be taken before the water is delivered into the mains. The hygienic significance of iron in water may be considered as *nil*, for, when present in large amounts, its undesirable taste would preclude its use.

Organic Matter. Under this heading, although it may not be precisely correct, we will include all nitrogenous matter, such as free and albuminoid ammonia, nitrites, and nitrates; and carbonaceous matter, such as 'oxygen consumed,' and the like; in short, all organic matter found in water, both of vegetable and animal origin, whether derived from human or animal excrement, or from the wash of woods and fields. It is necessary only to eliminate living bacteria from the discussion. These have been already considered.

There is nothing in the complex compounds of organic matter commonly found in water-supplies which need give alarm to the water consumer. Prior bacterial decomposition of such matters is doubtless instrumental in producing certain ptomaines, which in sufficient quantity would exert in some degree a toxic effect on the human organism. But while such conditions might be conceived of in sewage, in water, even after it has received sewage up to the limit of its powers of digestion, the dilution of such substances is too great to warrant serious consideration being given to this feature.

Chlorine. The chlorine found in water is not *per se* of great sanitary significance; but inasmuch as sewage and domestic wastes contain large amounts of salt, its presence in water-supplies indicates that it may have come from such sources. The chlorine, however, can only be attributed to animal organic pollution when other figures of the chemical analysis, *e.g.* ammonia nitrates, nitrites, etc., point to the probability of such an origin. Suspicion, however, is aroused when the chlorine in a particular water-supply is much in excess of the chlorine in waters in closely adjoining

neighbourhoods. The water-supplies of seaboard cities, even when unpolluted, are normally higher in chlorine than unpolluted inland supplies, due to the salt blown in from the ocean. In certain inland localities unpolluted water-supplies are high in chlorine due to mineral deposits in the soil. In some places maps are constructed on which lines are drawn connecting the districts the waters from which contain similar amounts of chlorine. These lines are termed 'isochlods.' Effluents from alkali or other industrial works may also be the cause of excess of chlorides. Therefore, like nitrogen, high amounts of chlorine in water merely furnish circumstantial evidence of dangerous pollution.

The effect of chlorine *per se* on the public health in the quantities usually found in water is *nil*. Thresh, however, is of opinion that as much as 70 qrs. to the gallon of salt should condemn the water for drinking purposes. The average individual consumes at the table each day many times as much salt as is ever present in a drinking-water supply. In the army, water unfit for drinking due to bacteria is often rendered fit for drinking by chlorination.

Carbonic Acid. The determination of free carbonic acid in water is of importance, as it is well understood that it is an active agent in the corrosion of metals, particularly iron and lead. 'Red water' troubles are often to be laid at the door of free carbonic acid, in some measure at least, and, where it is present in relatively large quantities, steps are often taken to remove it by adding lime to the water. Where coagulating chemicals are used, particularly where lime is not employed with the salts of iron and aluminium, which are more commonly used as coagulates, the determination of free carbonic acid furnishes valuable information, as with each grain of added coagulant there is a corresponding increase in the amount of free carbonic acid.

BIBLIOGRAPHY

(In addition to works quoted)

HUGHES, S.: *Treatise on Waterworks.*

HUMBER, W.: *The Water Supply of Cities and Towns.*

MIDDLETON, R. E.: *Water Supply.*

WALTERS, R. C. S.: *The Nation's Water Supply*, 1936.

WOODWARD, H. B.: *The Geology of Water Supply.*

CHAPTER VIII

BUILDING STONES

The importance of a practical knowledge of geology when dealing with building stones is so obvious that it would appear quite unnecessary to emphasise it. But, unfortunately, the study of rocks is frequently neglected by architects and engineers.

The engineer should be acquainted with the general structure of rocks, as well as with the situations whence the best materials may be obtained. He must study the manner in which any particular rock *weathers* in the locality whence it is obtained, and should have a knowledge of the physical qualities of rocks.

For example, granite is generally considered one of the most durable rocks, but in a climate in which heat and cold alternate, the felspar may decompose when exposed to wet.

Again, a stone which may be sufficiently durable if placed under water, may not be so if kept alternately wet and dry by the rise and fall of water in a river or on a tidal coast.

The action of *frost*, as described in Chapter I, Section I, should be carefully studied in the case of rocks. It is therefore abundantly clear that a careful investigation of the geological history and structure of the rocks of his district will frequently enable the engineer to avoid such expensive mistakes as importing materials which can be obtained, of similar quality and at a low price, on the spot. Moreover, the physical qualities and weathering properties of building stones should be studied at the quarry site, and not merely deduced from carefully selected samples.

SECTION I. IGNEOUS ROCKS

Granites

True Granite. The term 'granite' was formerly, and still is occasionally, very loosely applied; many rocks of entirely different nature being known by this name locally and in the building trade. For example, the so-called Mendip 'granite' is really a limestone; Ingleton 'granite' is a conglomerate; Furnace Lochfyneside

'granite' is a quartz-porphyry; Petit 'granite' is a Belgian limestone; and various trap rocks have often been known as granite, while rocks with a granitic structure, such as syenite, diorite, and gabbro, are often confused with granite. A true granite is one with granitic structure which contains not less than 60 per cent. of silica —that is, the total silica and not merely that of the free quartz. Other rocks with granitic structure are described under the heading of *Granitoid Rocks* below.

Characteristics of granite in the mass are bosses, joints, veins, dykes, rift, and grain. With the exception of rift and grain, these are referred to in Chapter II, Section I.

The tendency possessed by many granites to split more freely in one direction than another is due to what is called the *rift* of the stone; and the *grain* of granite is the direction in which it may be split with a degree of ease second to that of the rift direction. These features are fully described in *The Geology of Building Stones*, by J. Allen Howe—a valuable book for engineers.

Mode of Description. For practical purposes granites may be described according to (*a*) their structural characteristics; (*b*) their mineral constituents; (*c*) their chemical composition; (*d*) their physical characters.

Structural Characteristics. Granites are holocrystalline granular rocks and, as the size of the grains varies, may be described as *fine-grained*, *medium-grained*, *large-grained*, or *porphyritic* when, like that of Shap in Westmorland, they contain large and independent crystals of felspar scattered through the mass.

Most granites exhibit the characteristic *fluidal* or *flow-structure* (see Chapter IV, Section III), the mica and tabular felspars having a tendency to lie with their flat faces in one direction. More rarely *orbicular*, *spheroidal*, and *banded* structures are found (see Chapter IV, Section III).

Irregularities of structure may occur as:

(i) *Clots* or *veins*, which may be pegmatitic (see Chapter IV, Section III), may appear in the midst of the granite, and may or may not be composed of the same minerals as the rest of the granite.

(ii) *Drusy* cavities may occur lined with *geodes* (see Chapter IV, Section III), consisting of the same minerals as the surrounding rock.

(iii) Aggregates of the darker minerals known as *xenoliths* (or 'heathen' by quarrymen) may be found included in the mass.

Mineral Constituents. 'Not only do granites vary greatly in the

relative proportions of their mineral elements, but they also exhibit considerable variation in their constituent minerals. For although we may use the general formula of quartz, felspar, and mica to describe the rock, yet the felspar or mica may be almost any member, or members, of these families of minerals, and they may be supplemented or partly replaced by minerals which are no essential component of granite, and are local in their development.'[1] Granites may be grouped or described, according to the dominant mineral, as *biotite-granite*, with only dark mica; *muscovite-granite*, with only light mica; *muscovite-biotite-granite*, with both light and dark mica; *hornblende-granite*, with hornblende in lieu of mica; and similarly *tourmaline-granite*, *augite-granite*, etc.

Chemical Composition. When this is examined, the variation is almost as remarkable as that of the mineral elements; for 'although we may regard the normal composition as including silica, alumina, peroxide, and protoxide of iron, lime, magnesia, soda and potash, and water, yet sometimes in addition to these there are perceptible quantities of oxide of manganese, phosphoric acid, lithia, and fluorine, while not infrequently the protoxide of iron, or even all the iron, may be absent, as may be the magnesia and the water. Even in British granites the percentage of every constituent is very variable: thus the silica ranges from as low as 55·20 in the granite of Ardara to as high as 80·24 in the granite of Croghan Kinshela; so that, judged by this test, the Ardara rock might be termed basic, while the Croghan Kinshela rock is typically acidic.

'The alumina varies from 11·14 per cent. at White Gill, Skiddaw, to 20 per cent. in the granite of Glen in Donegal. The peroxide of iron ranges from ·23 at Botallack to 7·3 in some of the granites of Leinster; whilst the protoxide of iron, which is so frequently absent, amounts sometimes to upwards of 2 per cent. The lime varies from ½ per cent. in some of the Cornish granites to upwards of 5 per cent. in some of those from Donegal. The magnesia, which may be a mere trace, amounts to 3½ per cent. in the granite of Ardara. Soda may be but ½ per cent. in Cornish granite and 5½ per cent. in some of the Leinster rocks. Potash is less than ½ per cent. in one of the Leinster granites and more than 8½ per cent. in the granite of Chywoon Morvah in Cornwall. The manganese never quite amounts to 1 per cent., and the water is never more than 2 per cent.'[2]

[1] Phillips: *Manual of Geology*, Part I, H. G. Seeley, p. 203.
[2] Phillips: *Ibid.*, pp. 203–4.

Granites may therefore be described according to chemical composition as *alkali-granites, lime-alkali-granites, potash-granites,* or *soda-granites*, but this mode of description is not of much use to the engineer.

Physical Characters. Granites, like most rocks, are very variable, hence the following particulars are only of general application:—

Specific gravity varies from 2·6 to 2·8.

Weight per cubic foot varies from 160 to 200 lb.

Resistance to pressure varies from 800 to 2740 tons, but is usually between 1000 and 2200 tons.

Absorption of water, about ½ per cent.

Colour varies very much, some granites being white or grey, while others are pinkish, yellow, or green. The colour depends largely on the felspar, but partly on the extent to which they contain biotite or other dark-coloured minerals. Colour is no indication of the value of a granite for building purposes.

Durability. Granites differ much in durability—some varieties are very friable and liable to decomposition, while others suffer but imperceptibly from moisture and the atmosphere.

The chemical composition of a granite gives no idea of its physical properties. Part of the silica is free, part in the mica and felspar; part of the lime, soda, and potash is in the mica, and part in the felspar; the magnesia is in the mica. Granites containing an excess of lime, iron, or soda are most liable to decay, while those containing large crystals of mica, and those with an excess of soda-felspar or deep red (iron) felspar, are least fitted for building.

The proportion of felspar is important because the durability of the stone chiefly depends on this ingredient, although a large proportion makes the stone harder to work. Mica is a source of weakness as it is liable to decay. Iron, especially in the form of marcasite, is detrimental to durability and strength.

Since chemical analysis affords no proof of the durability of a granite, it is best to visit the quarry and inspect the weathering of old workings.

Quarrying. Granites as a rule have little or no superficial covering, and are quarried from hillsides or sloping ground. For small purposes they are usually blasted, but for large blocks they are split with wedges. Such large blocks are more easily obtained where the structure is massive, but in most quarries the granite is jointed, both vertically and horizontally. The vertical joints, which are either truly vertical or inclined at a high angle, run through

the rock often to great depths. They are generally constant in direction and in two sets at right angles. The horizontal joints split the rock into sheets or beds, which may be more or less horizontal or else follow the surface of the granite.

Granite, like all rocks, can be better dressed when still in possession of its *quarry water* or *quarry sap* (*cf.* Chapter I, Section I, 'Frost'; Chapter VII, Section II, 'Saturation,' etc.; and Section III of this chapter). This water of imbibition varies from 1 to 5 per cent. of the weight of the rock. The more absorbent the rock the less its durability.

Geological Age of Granite. Although granite was once thought to be the oldest of rocks, it is now known to have been formed at various periods extending from before the Silurian down to the Cretaceous.

The age of granite is always newer than the rock which it penetrates, and older than a stratum deposited upon it. It is rare to be able to fix both of these limits of age.

Distribution of Granites. For the distribution of granites and all other rocks, the reader is referred to *The Geology of Building Stones*, by J. Allen Howe (E. Arnold).

Granitoid Rocks

Syenite. For lithological characters, see Chapter V.

True syenites are limited in occurrence, but the name is used for other rocks similar in appearance but with quite different characteristics; *e.g.* the so-called syenite of Charnwood Forest is a syenitic or hornblende granite. It is rather coarsely crystalline, and contains dark green hornblende with pink and greenish felspar, with small masses of yellowish-green epidote and occasional grains of pyrites. When the rock is more finely crystalline it is generally of a red colour. The original syenite from Syene, Egypt, is now considered to be a hornblende-biotite-granite. Swedish syenite and Lansitz syenite from Spremberg, Prussia, are diabases, and Odenwald syenite is a diorite.

Qualities. The chemical constituents are similar to granite, but there is less silica. The entire absence or relatively small proportion of quartz is characteristic.

Specific gravity, 2·5–2·6.

Resistance to pressure—Average, 1170 to 1280 tons per sq. ft.
Maximum, 2200 tons.
Minimum, 730 tons.

Porosity coefficient about 1·3.

Durability equal to the best granite and better than those of moderate quality. Softer to work than granites, but quite as tough.

Gneiss (see Chapter V, Section III) is composed of the same minerals as granite, and differs from the latter chiefly in being foliated. When the foliation becomes indistinct, the rock approximates lithologically to granite. Rocks of this indeterminate character are styled *granitic gneiss*.

Gneiss resembles granite in its properties and appearance, but is not so durable or so strong. Its foliated character enables it to be got with comparative ease, and it furnishes good material for flagstones. Gneiss is used for ordinary building purposes in the districts in which it is found.

Porphyry. The three main varieties of porphyry—quartz-porphyry, granite-porphyry, and orthoclase-porphyry—are described in Chapter V, Section I. The term felsite-porphyry or felsite is sometimes used for a rock whose ground-mass is so fine that it is difficult to recognise the various constituents even with a high-powered microscope.

In all these varieties the essential constituents are orthoclase-felspar and quartz. The colour of these rocks varies from flesh-red, purple, yellow to slate-grey, depending chiefly on the felspar, while dark grey, brown, and greenish tints are imparted by the presence of mica or hornblende.

Specific gravity varies from 2·4 to 2·8. Resistance to pressure from 2740 tons per sq. ft. to 1645.

Average porosity is 0·65.

Absorption under pressure is between 0·9 and 3·5 per cent. of the weight.

The hardness and power of resistance to weathering depend to a considerable extent on the degree in which the ground-mass has been impregnated with silica.

The stone may be suitable for building even if the felspathic portion shows signs of alteration, but in varieties without quartz if a freshly fractured surface has an earthy appearance it should not be trusted.

Though hard and tough, these rocks are fairly easily quarried, but not so easily grained as granite owing to the absence of rift. They are generally polished with ease, and are used for ornamental work, such as mantelpieces, columns, etc. They are, however,

chiefly used for road metal, though also used in country districts for building.

The porphyries generally occur as dykes, and eruptive masses intersecting the older schists and slates, and are usually much fissured and jointed.

Porphyrites (see Chapter V, Section I). Their physical properties are similar to those of porphyry, but they are less bright in colour. They are used for road material, especially in Leicestershire, Wales, Scotland, and Belgium (Quenast Quarries).

Serpentine Rock. A siliceo-magnesian rock of metamorphic origin, arising apparently from the transmutation of magnesian limestones or other closely related strata. Its average composition is 40 per cent. of silica, 40 of magnesia, and 13 of water, with varying proportions of iron-peroxide and traces of other colouring matter.

Serpentine is not adapted for outdoor use, especially in towns, for it is acted on by hydrochloric and sulphuric acids, but it is very suitable for indoor decoration.

Crystalline Schists. Some of these old rocks have a granitoid appearance. They are described under 'Slates and Fissile Rocks' (see Section II).

Dolerites are basic hypabyssal rocks, but as their essential minerals and chemical composition are similar to basalts (see Chapter V, Section I), they are included with the latter under the general term of 'Trap Rocks' (see below).

Trap Rocks

The term *trap* was derived from the great sheets of lava which flowed out in successive streams, forming a step-like structure, in Norway, Faroe Islands, the Deccan, etc. It came to be used for the basalts and rocks known as whinstones, greenstones, felstones, and claystones, and is often still used in this sense for trade purposes.

Greenstone is an old name for the dark green, fine-grained rocks known as *diorite*, *diabase*, *gabbro*, and *aphanite*. The name is sometimes confined to diorite, but the more general designation is sufficient for practical purposes. These rocks all occur as dykes and veins, chiefly in the more ancient rocks. Their green colour is derived partly from their hornblende and partly from a small quantity of chlorite which is generally present. Gabbro is coarse-grained, diabase and diorite are fine-grained, and aphanite is very compact and fine-grained. They are all occasionally amygdaloidal,

and are no doubt varieties of the same rock solidified under slightly different conditions.

Diorite is tough and hard and of considerable strength, porosity 0·25 per cent., and of fairly high, weather-resisting quality, though the latter is diminished if pyrites are present. It is difficult to work, and only used as a building stone locally, but much used for paving and road metal.

Mica trap or *minette* occurs also in veins and dykes. It is tough, and weathers rusty brown.

Whinstone. Any very hard, dark-coloured rock that is not easily broken up in excavating, such as basalt, chert, or quartzose sandstone, is called a whinstone locally.

Basalt. These lavas have a dark colour on the newly fractured surface, varying through shades of greyish brown, blue, and greenish black; but when the external surface is weathered, the rock is commonly a pale drab, though the tint varies with chemical and mineral composition and texture. Basaltic rocks have a high specific gravity and basic composition. Their silica rarely sinks below 40 per cent., a lower percentage of silica is usually associated with large percentages of iron and sometimes of lime. The silica rarely exceeds 56 per cent. The alumina has no necessary relation to the silica, though the average amount ranges between 11 and 28 per cent. The lime, magnesia, potash, and soda all vary in amount, and on this variation depends the mineral composition of the rock. Basalt abounds in labradorite and augite, generally contains magnetite and olivine, and sometimes may have a little quartz and sanidine.

Basalts vary considerably in structure; the coarsely crystalline varieties, and those with a porphyritic structure in which large crystals of some mineral (phenocrysts) are embedded in a cryptocrystalline matrix, are essentially *dolerites*; the glassy forms are *tachylytes*, and the finely crystalline varieties may come under the head of *anamesites*; while those which appear homogeneous to the naked eye are classed as *basalts* proper.

Basaltic rocks vary very much in structure and composition. They may be soft, earthy, and amygdaloidal, compact, or highly crystalline. They possess a high power of resistance to crushing force, weigh from 171 to 181 lb. per cubic foot, absorb less than 4 oz. of water per cubic foot, and are very durable. They are suitable for paving and road metal, but not much used for building.

Lavas. The term 'lava,' properly speaking, includes all the

molten rocks of volcanoes (see Chapter I, Section II); but for practical purposes the basaltic rocks, which have been already described, are excluded, and 'lavas' denote only the lighter varieties such as trachyte, rhyolite, andesite, and obsidian.

Trachyte, rhyolite, andesite, and *phonolite* may for technical purposes be considered together. All vary very much in structure, from crystalline granular to glassy, as in obsidian, or vesicular, as in pumice. All the porous or vesicular varieties are suitable for building, forming, owing to their rough surface, a good bond with the mortar.

Phonolites are apt to weather into thin slabs which have been used for walling, roofing, and paving.

The lighter kinds of these rocks are suitable for arches. The heavier kinds are quarried in the British Isles for road stone.

Laterite covers considerable areas in S. India, Orissa, etc. It is a ferruginous material formed as a superficial alteration of rocks in regions subject to alternate wet and dry seasons. Weathering removes the silica of basalts, etc., and leaves a flaky ferruginous clay often containing manganese, which is soft and friable when fresh, but when exposed for some time hardens and becomes covered with a dark encrustation which protects the stone from further cleavage and resists decay. It is used for building and road metal.

Laterite should be compact in texture, and the mottled and streaked colours pervading it should not be very unevenly distributed. Those descriptions in which the sinuosities are numerous and deep, as well as those in which white lithomargic earth occurs, should not be used as building material. Laterite being benefited by long exposure should never be used when freshly quarried, especially from any depth. It should not be used where subject to any great pressure.

SECTION II. SANDSTONES, LIMESTONES, AND ARGILLACEOUS ROCKS

Sandstones

Lithological Character. 'These rocks consist essentially of grains of silica. They either occur as superficial accumulations of loose sand forming desert tracts, or low-lying districts on seacoasts, where the wind piles the sand up in dunes; or they may occur as beds of loose sand, interstratified with coherent beds of rock. They are also met with in a state of more or less imperfect consolidation,

the grains being feebly held together by an iron oxide or by calcareous matter; or they may be excessively hard and compact, the constituent grains being cemented by either silica, carbonate of lime, iron oxides, or carbonate of iron. In some few cases there even appears to be, according to Professor Morris, no cementing matter present, as in some of the New Red Sandstones, the constituent grains being apparently held together merely by surface cohesion superinduced by pressure.

'*Grits.* The rocks called grits vary considerably in lithological character. The term "grit" appears indeed to be very ill-defined. The Millstone Grit, which may be taken as one of the leading types, is more or less coarse-grained, while some of the Silurian rocks, such as the Coniston and Denbighshire grits, are frequently very fine-grained and compact in character. Under these circumstances it seems that a grit may best be defined as a strongly coherent, well-cemented, or tough sandstone, usually, but not necessarily, of coarse texture.' [1]

Quartzites are sandstones which have been converted into solid quartz-rock by the deposition, between the grains of the rock, of silica in the form of crystalline quartz. They are free from pores and have a smooth fracture. Most quartzites are found among ancient rocks. They are too hard and splintery to be used as building stone, but are much used as road material.

Liver rock is a term used in Scotland for a dense freestone which is grained in large blocks and has no natural division planes.

Colour and Structure. Sandstones may be coloured white, cream, yellow, fawn, pink, red, greenish grey, grey, or black. The white or cream colour is generally due to argillaceous or calcareous matter without any admixture of iron, the yellow, pink, and red to the presence of iron—limonite in the paler varieties and hæmatite in the reddish ones. Green, grey, and black colours may be due to carbonaceous matter.

These colours sometimes fade, and sometimes become darker, on exposure to the weather.

In structure, sandstones occur in every degree of fineness, from fine-grained sandstones to coarse-grained grits.

Composition. As mentioned in Chapter V, Section II, sandstones are described as *siliceous, quartzose, micaceous, ferruginous, calcareous*, and *argillaceous*; also *bituminous, carbonaceous*, or *felspathic*, according to the nature of the ingredients.

[1] Frank Rutley: *Study of Rocks*, 6th ed., p. 276.

Their chemical composition varies extremely, even in the same quarry.

Physical Characters. The *specific gravity* of sandstones and grits varies from 1·9 to 2·8; the *weight* per cubic foot from 130 to 160 lb.; the *porosity* ranges between 5 and 28 per cent.; and the *crushing weight* from 500 to 14,000 lb. per cubic inch.

Selection for Building. Many sandstones are so soft and disintegrate so rapidly when exposed to the weather that they are quite unfit for building, while others are so hard and siliceous as to be more suitable for road metal than for building.

For building purposes those which are fine in grain, most homogeneous in structure, with the least porosity, and the freest from lime and iron, are preferable. Any stone containing nodules of iron pyrites should be rejected, as such nodules oxidise and finally weather out into cavities.

Sandstones absorb moisture most easily in the direction of the bedding or grain, if there is any distinct bedding. Hence the blocks when used for a building or wall should be placed with the bedding horizontal. This position is, moreover, the one in which the stone will stand the greatest pressure. Bath stone is a case in point; at Bath the discoloration and bad weathering of faces of buildings is due to faulty laying of the stones.

The best method of ascertaining the durability of a sandstone is to observe exposures on cliffs, old quarries, etc.; porosity and other qualities can be tested as described in Section III of this chapter.

Limestones and Marbles

Limestones. *Lithological character.* Limestones used for building purposes include nearly all of the many varieties in which this stone occurs. Their essential characteristic is the presence of carbonate of lime ($CaCO_3$), which varies from 98 per cent. in pure varieties to 30 per cent. in impure kinds. This carbonate of lime is largely due to the calcareous shells of marine organisms, and, as the latter became more prevalent in later times, it follows that limestones are less frequently found in the older formations, and become more numerous in each successive geological age.

The varieties of limestone include the purer forms such as Chalk, and the less pure, of which the prefix, such as arenaceous, argillaceous, siliceous, dolomitic, or carbonaceous, denotes the dominant qualities.

Physical qualities, such as density, absorption, and resistance to pressure, necessarily vary so much in such very different varieties

of stone, that experiments are applicable only to the particular kind of stone tested. Specific gravity varies from 2·7 to 2·9, and crushing strength from 400 to 1400 tons per sq. inch.

In *structure*, limestones vary from earthy to compact or subcrystalline; many are thick-bedded and homogeneous and afford blocks of large size, while in others the uniformity of structure is interrupted by the remains of shells, etc.; others, again, are so jointed that they cannot be raised in blocks of any great size.

Subdivision. Limestones may be divided into:

I. Organically formed Limestones.

1. *Shelly limestone*, *e.g.* some of the Carboniferous and Lias, Portland stone (in part), Ham Hill stone (Inferior Oolite), Totternhoe stone (Lower Chalk); also Purbeck and Wealden beds of freshwater origin.

2. *Crinoidal Limestone*, *e.g.* bird's-eye marble (Carboniferous) and Petit granite of Belgium.

3. *Foraminiferal limestone*, *e.g.* the chalk and many beds of Carboniferous limestone in England, and the Nummulitic limestone of Europe, Africa, and Asia.

4. *Coral limestone*, *e.g.* Devonshire marble, etc. (Devonian and Carboniferous).

5. *Bryozoa limestone*, *e.g.* many of the magnesian limestones of Yorkshire.

II. Chemically formed Limestones.

1. *Tufa* or *Travertine*, *e.g.* in small deposits at various places in Great Britain, in Normandy, S. Italy, and notably in Rome (see below under 'Marbles').

2. *Oolitic limestones*, *e.g.* Portland and Bath stone, also among the Carboniferous limestones of Bristol, Derbyshire, South Wales, and Ireland.

III. Dolomite and Magnesian Limestones, *e.g.* in the Carboniferous limestone of Derbyshire, South Wales, Ireland, etc.

IV. Argillaceous Limestones. With increase of argillaceous matter these pass into calcareous slate or clay—found in all formations, specially in the Lias.

These stones are hard, smooth, and compact when freshly quarried, but do not weather well.

V. Arenaceous or Siliceous Limestones. These pass into calcareous sandstone with increase of silica, *e.g.* Kentish Rag and Beer stone. Many varieties are too hard to pay for dressing.

Marbles. 'Any rock susceptible of a fine polish is termed "marble" by the stone-cutter; hence we hear of "Connemara marble," which is a true serpentine; and of "Sicilian marble," which is often a brecciated lava. The term, however, should be, and is, restricted by geologists to limestones capable of receiving a polish, and frequently exhibiting a variety of colours in veins and blotches. We have thus *uni-coloured* marbles, such as pure blacks and whites; and *parti-coloured* sorts, deriving their tints from accidental minerals, from metallic oxides, giving them a veined or clouded appearance, or from shells, encrinites, corals, and other organisms which impart a variety of "figure" as well as of hue.

'The following are a few of the better-known and more esteemed varieties, ancient and modern: *Carrara*, pure white, saccharoid, and semi-transparent; highly esteemed for statuary purposes. *Parian*, of a waxy cream colour, also crystalline and employed in statuary. *Giallo-antico*, yellow and mixed with a small proportion of hydrate of iron; used for ornamental purposes. *Sienna*, a rich yellowish brown, with lighter veins and cloudings. *Rosso-antico*, a deep blood-red, more or less veined. *Mandelato*, a light red, veined and clouded. *Verde Antique*, a cloudy green, mixed with serpentine, or serpentine itself. *Cipolino*, a mixture of talcose schist with white saccharoidal marble. *Bardiglia*, a bluish-grey variety with bold black veins and cloudings. *Lumachella* or *fire-marble*, a dark brown variety, having brilliant chatoyant reflections, which it owes to the nacreous matter of enclosed shells. *Black marbles* like those of Derbyshire, Dent, and Kilkenny, deriving their dark colours from bitumen. *Encrinal marbles*, like those of Dent in Yorkshire and other Carboniferous districts, deriving their "figure" from the stems and joints of encrinites. *Shell marbles*, like those of Purbeck and Petworth in Dorset and Sussex, and Kingsbarns in Fife, receiving their "figure" from the component shells of univalves and bivalves.' [1]

Landscape marble is a close-grained limestone with dendritic marking.

Onyx marble is a laminated compact variety of calcite deposit in the form of tufa or travertine,[2] and under 'Chemically formed Limestones' above). It is largely used as a marble.

[1] David Page: *Economic Geology*, pp. 81–82.

[2] The terms travertine, calcareous tufa, and calc-sinter are generally considered synonymous, but Merrill limits travertine to the compact laminated deposit, and calls the porous variety *tufa*.

'The marbles are among the most varied and useful of rocks whether for external structures or for internal decoration. They are sufficiently durable in dry and pure atmospheres; can be raised, for the most part, in blocks of any size; and are easily tooled and polished. As building stones they are unsuited to our climate; hence their use is chiefly for interior decoration. Statuary marbles of the finest hue and texture are brought from Italy and Greece (Carrara and Paros), as are also many of the parti-coloured varieties for internal decoration. Some beautiful marbles are also obtained from Belgium and France, but several useful sorts are derived from the formations of our islands, as shown below.' [1]

Clays, Slates, Shales, and Other Fissile Rocks

Argillaceous Rocks. 'These rocks are, chemically speaking, impure hydrous silicates of alumina. Sometimes the impurity consists of sand, sometimes of carbonate of lime; and more or less carbonaceous matter is in many cases present. Their coarseness of texture is mainly dependent upon the coarseness of the sand which often occurs in them. When free from sand, they are usually of fine texture. They have all originally been deposited as mud, in most instances at the bottom of the sea, in others at the bottoms of lakes or as deltas, and exceptionally over land, when temporarily flooded by the overflow of rivers, as in the case of the Nile. Clay deposits often have a well-laminated structure, and, in the older geological formations, have assumed a more or less indurated character, frequently accompanied by a tendency to split along the planes of bedding. Very often another and more strongly marked fissile structure is superinduced in directions cutting across the planes of stratification at various angles. This is slaty cleavage, described in Chapter IV, Section III. Those argillaceous rocks, which split parallel with the planes of lamination or bedding, are called shales or flags, but the term *flag* is applied to a rock of any character which splits among its bedding into large flat slabs, and consequently it is common to find the term used to denote sandstones which are sufficiently fissile, when quarried, to yield slabs or flags.' [2]

Slate. The term 'slate' is frequently used as indicative of fissile structure rather than of lithological character. It is applied

[1] David Page: *Economic Geology*, pp. 81–82.
[2] Frank Rutley: *Study of Rocks*, p. 282.

to argillaceous rocks, *i.e.* clay-slates which split in directions other than that of their bedding, as well as to *fissile sandstones* such as the Collyweston 'slates,' and shales, which split along their planes of bedding, and also to *schists*, which split like clay-slates but are not argillaceous and are more highly *metamorphosed* than clay-slate.

Qualities of Clay-slate. 'A good slate is little absorbent of water, cuts freely but toughly, weighs from 160 to 180 lb. per cubic foot, and should resist a crushing weight of from 20,000 to 25,000 lb.

'For thinness, lightness, and straightness the Welsh slates are unequalled, but the Irish and the Lake District varieties are harder, heavier, tougher, and more durable; while for strength and solidity the Scotch are perhaps superior to either, but sometimes contain iron pyrites.'[1]

The best slates are obtained from various parts of North Wales, near the coast; from Delabole, Tintagel, and elsewhere on the north coast of Cornwall; from various parts of Cumberland; and from the west coast of Scotland, generally from quarries of great magnitude. The best slate slabs are from Wales.

In addition to trial as to water absorption, a close examination as to the presence of *pyrite* or *marcasite* is required before deciding that a clay-slate is fit for use, however even its fissile structure may be. The kinds with a glossy surface are most likely to be impervious to moisture, but they may be too brittle for good roofing slate.

Tests. Slates should resist *corrosion by acids* in the atmosphere. They may be tested by immersion in a weak solution of hydrochloric and sulphuric acids in equal parts. *Toughness* may be ascertained by subjecting the slate to deflection. *Transverse strength* is often important and is measured in the usual way (see Section III, 'Testing Stones').

Selection of Quarry. It is not usual to find slates and slabs in good condition near the surface, where long exposure to the weather has usually disintegrated and even destroyed the texture, and often, by partial hardening, obliterated or obscured the cleavage. As it is, however, entirely from the superficial rock and its geological condition that a judgment must be formed, a certain amount of experience, combined with a knowledge of the material, enables the geologist to judge well of the chance of a valuable quarry. Uniformity of texture and condition of the rock for considerable

[1] David Page: *Economic Geology*, p. 65.

distances, the nature and condition of the cleavage, the direction of the cleavage planes, the nature of the small veins of other material pervading the slate (of which there are always many), the presence or absence of iron pyrites, the direction and magnitude of the joints —these are the chief points concerning which careful investigation is necessary. But any or all of these are altogether insufficient to communicate value to a property unless the essential point of cheap and ready conveyance to a large market can be secured, and the quarries are so situated that the waste can be disposed of, and the valuable part of the slate laid bare without great expense.

Shale is distinguished from slate by its softer nature, its relation to the adjoining rocks, and the easy separation of the laminæ. Moreover, it is fissile only along bedding planes.

Shale is only an encumbrance and a nuisance to the engineer.

Fissile sandstone possesses no true cleavage. The rock is generally highly micaceous or calcareous. The *Collyweston* slates, and the *Dunton* and *Stonesfield slate* of the Lower Oolite, are well-known examples. Among the Coal Measures thin flaggy stone-tiles are obtained, and the *Horsham* stone of the Wealden is also fissile. Some fissile limestones occur. The flagstones of Caithness and Yorkshire are mentioned under 'Sandstones' above.

Schists. 'These old rocks generally occur in a slaty or fissile state, and are better adapted for roofing, paving, and other slab purposes than for building; and yet some of the compacter beds of the Silurian (the greywackes) make not a bad building stone (Keswick, Kendal, Hawick, Galashiels), being flat-bedded and easily squared and jointed. Where obtainable, a frontage of this sort is greatly improved by light-coloured sandstone dressings. In some districts, where sandstones and limestones are scarce, the mica-schists, gneisses, and chlorite-schists are employed for building purposes; but, though tough and durable, they seldom produce anything like a satisfactory effect.'[1] They may be formed from igneous rocks, or from limestone, sandstone, etc. Quartz is nearly always present, and the other prevailing minerals, *e.g.* mica, chlorite, hornblende, etc., are generally found in distinct layers along which the rock splits. Mica-schists are the most common.

[1] David Page: *Economic Geology*, p. 80.

SECTION III. WEATHERING, QUARRYING, AND TESTING STONE

The suitability of a stone for building purposes depends on its durability, colour, appearance, and cost. Colour is referred to in Chapter V, Section IV, while cost depends on many factors outside the scope of this book. Durability, or capability of wearing well under exposure to the weather, depends on the following considerations which come under the head of 'Weathering.'

Weathering

The processes effecting the decomposition of rocks are referred to in Chapter V, Section IV.

The attacking agents in the weathering of rocks are referred to in Chapter I, Section I, and are all, directly or indirectly, atmospheric. Even in the country the carbonic acid in the air attacks stone containing lime and the oxygen attacks stone containing iron, but in cities the atmosphere is often polluted with all sorts of acids, from smoke and 'works' of various kinds. Moreover, in all cases the weathering action is greatly accelerated when the air is moist, and frost has a destructive effect.

The direct action of the wind often has a destructive effect by blowing sharp particles against the stone with a grinding action. Variations of temperature, too, affect stone by causing expansion and contraction.

The **resistance** of stone to these attacks depends on (*a*) its *chemical composition*, which must be such as will withstand the particular acids which may be present in the district; (*b*) the *physical structure*, *e.g.* crystalline, non-porous, and fine-grained rocks offer more resistance than non-crystalline, porous, and coarse-grained rocks, and where there is any cementing material, only a stone whose grains and cement are of lasting material will be durable; (*c*) the *position of the stone* in a building may influence its durability, *e.g.* stone on a side of a building on which rain mostly comes, or where sheltered from the sun and wind, so that moisture does not dry easily—such as the shady side of jambs, soffits of arches, lintels, etc., will not last as long as where exposed to sun and wind.

Weathering Properties of Sandstones and Limestones. The decomposition of stones employed for building purposes is greatly influenced as well by the chemical and mechanical composition of

the stone itself and by the nature of the aggregation of its component parts, as by the circumstances of exposure. The oolitic *limestones* will thus suffer unequal decomposition unless the brittle, egg-shaped particles, and the cement with which they are united, be equally coherent and of the same chemical composition. The shelly limestones, being chiefly formed of fragments of shells, which are usually crystalline and cemented by a calcareous paste, are unequal in their rate of decomposition, because the crystalline parts offer the greatest resistance to the decomposing effects of the atmosphere. These shelly limestones have also, generally, a coarse laminated structure parallel to the plane of stratification, and, like sandstones formed in the same way, they decompose rapidly when used as flags, where their plane surfaces are exposed; but if their edges only are laid bare they will last for a long period.

Sandstones, from the mode of their formation, are frequently laminated, and more especially so when micaceous, the plates of mica being generally deposited in planes parallel to the beds. Hence, if such a sandstone, or shelly laminated limestone, be placed in a building with the planes of lamination in a vertical position, it will decompose in flakes, more or less rapidly, according to the thickness of the laminæ; whereas if placed so that the planes of lamination are horizontal, that is, as in its natural bed, the edges only being exposed, the amount of decomposition will be altogether immaterial. The sandstones being composed of quartzose or siliceous grains comparatively indestructible, they are more or less durable according to the nature of the cementing substance; while, on the other hand, the limestones and magnesian limestones are durable in proportion to the extent in which they are crystalline, those which partake least of the crystalline suffering most from exposure to atmospheric influences.

The chemical action of the atmosphere produces a change in the entire matter of limestones, and in the cementing substance of sandstones, according to the amount of surface exposed. The mechanical action due to atmospheric action occasions either a removal or a disruption of the exposed particles: the former by means of powerful winds and driving rains, and the latter by the congelation of water forced into, or absorbed by, the external portions of the stone. These effects are reciprocal, chemical action rendering the stone liable to be more easily affected by mechanical action, which latter, by constantly presenting new surfaces, accelerates the disintegrating effects of the former.

Injurious Minerals. *Flint* or *chert* is harder than the surrounding rock, and therefore resists the weather better and tends to stand out on the weathered surface. Cherty rocks are liable to split along the line of the concretions. *Mica* in granite, if in excess, is likely to induce splitting along the lines of foliation; if present in crystalline, limestone, or marbles in any quantity, it weathers out and causes pitting and spalling. *Pyrite* is apt to weather on exposure into limonite, and to develop pits. *Tremolite*, which is found in some magnesian limestone, on exposure decomposes into clay.

Destructive Agents. *Lichens* protect most stones and increase their durability, but give out carbonic acid which, when dissolved by rain, attacks limestone.

Molluscs—Pholas dactylus and *Saxicava*—bore holes in limestone, clay, shales, and sandstones, and weaken them.

Appearance, especially for face-work, is important. Varieties of stone containing iron should not be used, nor those with any flaws or clay-holes, while mottled or blotched coloured stones should be viewed with suspicion as likely to weather unequally owing to want of uniformity in chemical composition.

Quarrying

Quarrying is an art which can only be learnt by experience. When stone can be obtained from established quarries, it will suffice for the engineer to know how to inspect stone at the quarry and what kind of stone to specify. When new quarries have to be opened, *e.g.* in India and the Dominions, etc., the engineer will often be compelled to make all the necessary arrangements, as the methods of native quarrymen are often very rudimentary.

Quarry Site. The first step is to ascertain whether the stone is suitable for the purpose for which it is intended. The remarks under 'Weathering' above should be studied, and samples of both weathered and fresh rock should be examined as described in Chapter VI and under 'Testing Stone' below.

Almost all rocks have some kind of joints or division planes (see Chapter II, Sections I, II, and III), and as the art of quarrying depends to a great extent on taking advantage of these division planes, quarry sites should be sought for where they are well developed. A quarry is usually worked to the dip of the rock,

the strike-joints being known as 'backs' and the dip-joints as 'cutters.'

The process of stripping the quarry consists in removing all dirt and disintegrated material from the rock-face. Frequently, as on hillsides, a ledge of rock is exposed so that very little stripping is required, and in selecting a quarry site this point should be considered. Hillsides are the most favourable sites for quarries.

If the stone is found suitable, facilities as regards communications and water are the next consideration. For important quarries railway sidings are essential, and water is required for the workmen as well as for boring, and for engines, etc.

In mountainous districts in India there is often a difficulty in finding hard stone conveniently near to where it is required for work. The hardest stone is to be found at synclines, where the pressure due to folding is greater. The opposite is the case at anticlines.

When it is necessary to get stones up to high ground the cost of the stone is increased, and contractors will, unless they are pervented, use quarries on anticlines, owing to the stone being easier to quarry and cheaper to transport to the work.

Position in Quarry. In order to obtain the best stone from a quarry it is often essential to take it from some particular stratum, for it may happen that in the same quarry some beds are much better than others, while some are workless, though all may be similar in appearance.

Seasoning. Most stone improves by being seasoned by exposure to the air, thus getting rid of the 'quarry sap' (see Section I above, *Granites*: 'Quarrying'). In hot climates, however, it is sometimes advantageous to retain the quarry sap, as it makes the stone easier to cut and prevents the moisture being drawn out by the mortar. In cold climates it is desirable to get rid of the moisture to prevent the stone being cracked, or even disintegrated by the action of frost.

Natural Beds. Except in cornices, corbels, etc., stones in walls should be placed on their natural bed. In arches, the natural bed should be at right angles to the thrust. Since beds are often tilted, the original natural bed must be carefully sought for. The natural bed can be traced in some stones from the embedded shells, which must have been deposited horizontally.

Testing Stone

Where a suitable laboratory is available, detailed examination of building stone should be left to the chemist. At the same time it must be remembered that laboratory tests carried out on selected samples are only of general application. In the case of established quarries the most practical test is to examine buildings made of the stone. If the stone has good weathering qualities, the faces of the blocks even in old buildings will exhibit no signs of decay, the arrises should be sharp and tool-marks should be visible.

Some of the simpler tests can be carried out by the engineer. The *broken surface* may be examined by a powerful glass, and should show a sharp, bright, and clean fracture. Usually the densest and strongest stones will prove the most durable, hence *specific gravity* should be ascertained. The importance of *crushing strength* has been overestimated, for the pressure on stone used in building seldom, if ever, approaches the actual crushing strength; but the crushing strength gives an indication of the resistance to frost. Building stone is occasionally subjected to tension, hence *transverse strength* may be important. The *porosity* or volume of pore space, and *absorption* or amount of water which a stone will absorb when immersed, are valuable indicators of frost resistance. *Hardness* is of importance.

Crushing Strength. Samples, usually 2-inch cubes, are subjected to gradually increasing pressure until the stone breaks down. The cubes should be true and rubbed smooth, and should be dried at a moderate temperature. The cubes should be cut so that the pressure can be applied perpendicular to the rift (*cf.* Section I, Characteristics of Granite). The results obtained are very variable, and tables given by different authorities vary considerably. The following values may be of interest:—

Granite	varies from	13,000	to	28,000	lb. per	sq. in.
Sandstone	,,	6,000	,,	18,000	,,	,,
Limestone	,,	4,500	,,	12,000	,,	,,
Marble	,,	10,000	,,	22,000	,,	,,
Slate	,,	10,000	,,	15,000	,,	,,

Transverse Strength. This is measured by the use of the formula

$$R = 3\frac{wl}{2bd^2}$$

where R = modulus of rupture per sq. in.
w = weight required to break stone.
l = distance between supports.
b = width of stone.
d = depth of stone.

Weight. The weight of stone may be important. It depends on the specific gravity, porosity, and amount of water contained when weighed.

Density, or the weight of unit volume of stone inclusive of pores, is important as an indication of absorption. It varies with the weight.

Absorption and Porosity. The difference between absolute porosity, or the ratio of the volume of the pores to the volume of the stone, and relative porosity, or the ratio of absorption, must be borne in mind. There is not necessarily any fixed relation between the two, but a stone of low porosity can absorb but little water, while a stone of high porosity will absorb much water but will not retain it if the pores are large, as the water drains off.

Porosity can be ascertained from the formula

$$P = 100\frac{W - D}{W - S}$$

where P = volume of pores in percentage of volume of stone.
W = weight when saturated.
D = dry weight.
S = weight of saturated stone when suspended in water.

To effect saturation the stone should be immersed for twenty-four hours, and the surface should be dried when taken out.

Resistance to Frost. This depends to some extent on the size of the pores, and whether they are straight or winding. If winding, water is held and action of frost intensified.

The splitting of a stone under the action of frost may be due to quarry water and not necessarily to absorbed water. The engineer should endeavour to escape trouble due to frost by selecting a stone of well-known frost-resisting power, by avoiding quarrying stratified stone in cold weather, and by not placing porous stone in a position where it is exposed to moisture.

Brand's Test. This test may be used to determine the resistance of stones to frost. It is especially adapted to oolites and other calcareous rocks. Cannot be applied with any certainty to other rocks.

1. Several specimens should be selected from a block of stone to be tried, taking, for instance, those which present differences of colour, grain, or general appearance.

2. These fragments should be cut into 2-inch cakes, with sharp edges, and each marked carefully.

3. A saturated solution of Glauber's salt (sulphate of soda) is then to be boiled and the cubes submerged, and retained in the boiling liquid for half an hour. If a longer period elapse, the effects exceed those of ordinary atmospheric action and frost.

4. The specimens are then withdrawn and hung up in the air, and beneath each is placed a vessel containing a quantity of the solution in which it has been boiled, care being taken that it contains no fragments of the stone detached during the boiling.

5. If the weather is not too wet or too cold it will be found that the surface of the stones, twenty-four hours after they have been suspended, are covered with small white acicular crystals of salt. When these appear, the cubes are to be plunged into the vessel below them, to get rid of the efflorescence; and this is to be done repeatedly, as often as crystals of the salt are thrown out during the experiment.

6. If the stone resist the decomposing action of damp and frost, the salt does not force out any portions of the stone with it, and neither grains, laminæ, nor other fragments of the stone are found in the vessel. If, on the other hand, the stone yield to this action, small fragments will be perceived to separate themselves, detached, even from the first appearance of the salt, and the cube will soon lose its angles and sharp edges. The cubes are weighed at the end of the experiment and the difference noted. The experiment should last four days.

Resistance to fire can best be tested by building a piece of wall and subjecting it to intense heat.

Hardness. This quality is often important, as in pavements, quoins, dressings, etc., and hardness combined with toughness is essential for good road metal. It does not follow because a stone is hard that it will weather well, as many hard stones are more liable to be affected by the atmosphere than others of softer nature but whose chemical composition makes them less liable to decompose.

BIBLIOGRAPHY

(In addition to works quoted)

ALLEN HOWE, J.: *The Geology of Building Stones.*
LUARD, Major-General C. E.: *Stone: How to Get It and How to Use It.*

CHAPTER IX

BRICKS AND CLAYS

CLAYS

Clay is described in Chapter V, Section II, but we may mention here that, in common parlance, the term ' clay ' is used to denote any earthy substance which can be worked up with water into a plastic mass, and will retain its shape more or less perfectly when dried by heat.

All the clays are essentially alumino-silicic acids more or less mingled with impurities, and coloured by the presence of metallic oxides and organic matter. Generally speaking, they are soft and sectile; emit, when breathed upon, a peculiar odour known as clayey or argillaceous, and possess the capability of becoming plastic when mixed with a suitable quantity of water, and of losing this plasticity on being heated to a dull redness. Clay is seldom found pure, but, so long as the other materials with it do not interfere with its use for certain industrial purposes, such as the manufacture of bricks, it may for convenience be termed ' clay.'

As the chemical analysis of a clay only indicates its constituents and their percentages, and does not give any idea as to the way in which the atoms are arranged, clays with the same analysis may give widely different results.

ORIGIN OF CLAYS

Pure clay does not occur in Nature in a free state. The purest clay obtainable is prepared by the most careful washing of the purest natural clays. Perfectly pure clay is, therefore, a theoretical substance.

Kaolinisation. Clays are chiefly derived from felspathic rocks, principally granites, though syenites, gabbros, and trap rocks also furnish the raw materials from which some clays are formed. Although the various felspars may be regarded as the chief primary source of clays, there are many other minerals and rocks which can become secondary producers of clay, *e.g.* hornblende and augite.

The production of clays from igneous rocks is termed *kaolinisation*, and is chiefly effected by the removal of alkalies from the felspars by the solvent action of water (with or without dissolved substances), but some other forces appear to have been at work and to have made the rocks capable of being attacked in this manner. As the kaolinisation occurs most prominently at great depths from the surface, it cannot be due entirely to weathering, but is probably due to the action of fluorine, boron, or carbonic acid and water.

Constituents of Clay. The chief constituent of all clays or earths possessing actual or potential plasticity is known as *kaolinitic matter*, *clayite*, or *true clay*, while many clays contain a small quantity of *kaolinite*, which is a well-defined crystalline mineral. Both kaolinite and kaolinitic matter have practically the same chemical composition.

Kaolinite occurs only in small proportions. The crystals have a composition corresponding very closely to the purest china clays, and represented by the formula $Al_2O_3SiO_22H_2O$. Many clays are, however, destitute of matter which can be called crystalline.

Kaolinitic matter is obtained in its purest form by washing high-class china or ball clays and collecting the finest particles. Even then it always contains small quantities of iron oxide, lime, magnesia, potash, and soda, but if obtainable in a perfectly pure condition it would apparently be composed of about 46 per cent. silica, 40 per cent. alumina, and 14 per cent. water.

Kaolinitic matter is usually more fusible than the kaolinite crystals, and becomes plastic more readily on rubbing with water.

Kaolin or **China Clay** is a white earthy substance which is the final product of the decomposition of pure orthoclase and other felspars (see *Kaolinisation* above).

Kaolin took its name from the hill from which the Chinese in old times took their china clay, but the term is now used for partially plastic clays which turn white when burnt, and are found near the rock from which it appears that they were formed. For practical purposes kaolin may be taken as the equivalent of china clay.

The use of the term kaolin for true clay or clayite is incorrect nor should it include china clay rock.

In some parts of the world kaolins are found pure enough to be

used without preparation, but as a rule they have to be carefully washed.

China Stone or **Cornish Stone** is, strictly speaking, a partially kaolinized felsitic granite or pegmatite. It has various local names, such as *Elvan*, *Growanstone* (see Chapter V, Section II), and *St Stephen's Stone*, which are often applied, somewhat carelessly, to other granites. It is valued as a flux, and corresponds to the Chinese *Petuntse*. On complete decomposition it passes into a heterogeneous mass of which china clay is the most important ingredient.

China Clay. See under 'Varieties of Clays.'

China Clay Rock (carclazite) is a soft granite easily broken up by the weather and sufficiently decomposed to be treated for the removal of its contained china clay. It usually contains only about 20 per cent. of clay, the remainder being about 15 to 20 per cent. of mica and about 50 per cent. sandy quartz. Occasionally portions containing as much as 50 per cent. of china clay are found, particularly from the greatest depths.

British Clays. 'Of the clays used in this country for economic purposes may be mentioned the china clays or kaolins of Cornwall, which have been formed from the decomposition of the felspathic constituents of granite; the Watcombe clay, which occurs in the Trias, and is now used in the manufacture of pottery; the calcareous Liassic clays, used for brick-making and burning for lime and hydraulic cement; the various clays of Oolitic and Neocomian Age, some of which are used for brick-making, etc.; the Gault, the clays of the Woolwich and Reading beds, and the London clay, all of which are used for bricks; the celebrated Poole clay, dug at Wareham, which belongs to the Bagshot series, and is extensively used for pottery. The clays of the Bovey beds, large quantities of which are annually shipped at Teignmouth, afford good pottery clays and pipeclays. There are also many brick-earths and clays of post-Tertiary Age which are extensively used for brick-making and other purposes.' [1]

The majority are superficial deposits occurring in estuaries, desiccated lake-sites, river-valleys, and upraised sea-beds, or scattered over the surface as drifts or boulder-clays.

The river-mud in the Medway and at the mouth of the Thames is largely used in the manufacture of Portland cement, after being artificially mixed with chalk and burnt.

[1] Frank Rutley: *Study of Rocks*, pp. 284–5.

Qualities of Clays

Plasticity is one of the most important qualities. A material is said to be plastic when it can be kneaded or pressed into any desired shape, and remains in that shape when the kneading ceases or the pressure is removed; this alteration of shape being capable of being repeated indefinitely. Very few people agree exactly in their conception of plasticity. Thus a brickmaker terms a clay plastic when it will work well in his machine and is capable of being kneaded into a 'good' paste, but a potter usually places more emphasis on the binding power of a clay, though he terms this its plasticity.

It may be here noted that it is the combined water which gives kaolin its plasticity. If this be driven off by strong heat the residue is no longer plastic. This water, for instance, is expelled in the burning of bricks, and though powdered brick will absorb a great deal of water, it is impossible to make it in the least degree plastic by any amount of water. The degree of plasticity seems to depend largely on the fineness of the particles.

The *binding power* of a clay is the property it possesses of uniting with non-plastic material and water to form a uniform plastic paste, and is consequently closely related to its plasticity

'*Fat*' and '*Lean*' *Clays.* Clays with a high binding power are known technically as 'fat' clays; 'lean' clays are deficient in binding power.

Fat clays possess a high degree of plasticity, and are characteristically unctuous to the touch. They usually shrink on burning, and, unless carefully treated, are likely to crack and split. Lean clays usually contain a considerable proportion of free silica or chalk (see Loams, Marl, etc., below), and consequently they shrink but slightly in drying and firing.

A fat clay may be made lean by the addition of any suitable non-plastic material, grog or fine sand usually being employed, though in some districts chalk is used on account of its accessibility.

When excessively lean, a clay is too weak to retain its shape if made into vases, etc., but for articles of simple form, such as bricks and tiles, the leaner the clay the better, for it may be dried more rapidly.

'*Long*' and '*Short*' *Clays.* The term 'short' is sometimes used as synonymous with 'lean,' but it should preferably be used for clay pastes which break off suddenly when pulled asunder,

without the usual tapering extension shown by highly plastic clays. In the same way 'long' clays are those possessing considerable ductility or tenacity.

'Strong' and 'Mild' Clays. The term 'mild' is also sometimes used as synonymous with 'lean,' but is better used in contradistinction to the 'strong' surface clays with high plasticity, great toughness, and excessive shrinkage.

The **stickiness** of certain clays (*e.g.* London clay) is very pronounced, but must not be confused with true plasticity. Ashley has stated that if the granular constituent is removed from a plastic body it loses plasticity and becomes sticky until the granular constituent is restored. This suggests that the practice of adding granular material of a non-plastic nature, so common amongst users of London clay, is based upon a sound principle. Sticky clays are difficult to mix with water, and crushing rolls of special design must be employed.

Toughness and stickiness are commonly associated, and cause much difficulty when a uniform, homogeneous material is required, as a tough, sticky clay permits the rollers used for crushing to slip, unless they are specially designed to obviate this difficulty.

Oiliness is a characteristic of some clays, and is distinguished from stickiness in the smoother feel and less adhesiveness of the material.

Sectility, or the capability of being easily cut, is a characteristic of clays which occur in a plastic condition, such as ball clays and many surface clays. This property often serves as a simple means of distinguishing 'clays' from many other minerals, though the 'clays' so found may not be of any commercial value. Anyone constantly engaged in examining clays soon learns to recognise certain varieties by their sectility and by the slightly glossy appearance of the freshly cut surface, though these cannot be clearly described.

The **odour** of clay is indescribable though characteristic, and is most observable when the material is freshly cut. The source is not positively known, but is ascribed to organic substances in the clay.

The **specific gravity,** density, or relative weight of a clay is of theoretical rather than of practical importance.

The term **density** is occasionally used to indicate impermeability, a sample of clay being, in this sense, said to be dense because water will not penetrate easily into it.

The **refractoriness** of a clay is its power to resist the action of heat under a steadily rising temperature and in the absence of disturbing conditions (cf. *Fusibility*, below).

Clays vary greatly in their refractoriness, some very calcareous marls fusing at a red heat, whilst high-grade fireclays and china clays have a softening-point above 1800° C.

Refractory clays are of two kinds: (1) those containing nearly as much alumina as silica, and (2) those in which the silica largely predominates. The former are neutral and the latter acid, and should be used only in contact with acid materials.

Pure silica is nearly, but not quite, as refractory as pure clay, and sometimes mixtures of clay and silica are quite refractory so long as they are pure. Directly a small percentage of lime, magnesia, iron, or alkali enters into the composition of the mixture, the refractoriness is seriously diminished.

The texture of a clay is important, as the smaller the particles the more easily will the clay fuse, since they enter more quickly into reaction with the fluxes than do the coarser particles.

According to the purposes for which it is required, articles made of a refractory clay must be burned to an open or porous mass, a mass with an open interior but a dense surface, or as dense a material as can be produced, and clays of corresponding density should therefore be selected when possible.

Contraction or **Shrinkage** is chiefly, but not entirely, due to the removal of water from clay by evaporation at the ordinary temperature (air shrinkage), at a somewhat higher temperature in a dryer (dryer shrinkage), or during the burning (kiln or fire shrinkage).

The general idea is that as the water is removed, that which remains draws the clay particles together into a smaller and denser mass. If the clay is not subjected to draughts, the contraction will take place equally in all directions and the shape of the article will be retained. Highly plastic clays are extremely difficult to dry satisfactorily, as they shrink irregularly and set up internal strains which may easily cause the articles to crack.

The amount of shrinkage appears to depend upon the rate at which the clay is dried, for if this operation is performed rapidly the shrinkage will be less, the clay particles not having time to move over each other so freely as when the drying is slower. Rapid drying tends to crack dense clays, owing to the particles near the outer surface contracting more than those near the centre of the

article. Hence it is necessary to determine the best conditions of drying a given clay.

Colouring. 'The varied colouring of clays (and other rocks) is due to the presence of iron in various states of oxidisation, and to organic matter. The latter colours the clay from light grey to black. The former, in the state of anhydrous peroxide, imparts the deep reds which, on becoming hydrated, change to bright yellow, while intermediate conditions and concentration of the iron give shades of brown and purple. The grey clays so largely developed as clutches and fireclays in the Coal Measures owe their colour, in addition to the presence of carbonaceous matter, to carbonate of the protoxide of iron in a fine state of subdivision, and occasionally to the presence of finely divided bisulphide of iron. In the white and light grey clays, iron occurs principally in the form of carbonate of the protoxide. It has also been shown that many clays contain a notable proportion of titanic acid.' [1]

Chemical Properties. Pure clay is insoluble in dilute hydrochloric, nitric, or sulphuric acid, but is readily decomposed by boiling sulphuric acid and hot solutions of soda or potash. It may also be decomposed and rendered soluble by fusion with alkalies, or with alkaline carbonate, or with lime and ammonium chloride.

The effects of the different constituents of clay are described below (see 'Impurities in Clays' below).

The value of an ordinary (ultimate) chemical analysis consists chiefly in showing the presence or absence of an excess of any desired constituents—as the alkalies, lime, magnesia, and titanium oxide in a refractory clay, the iron in a buff-burning clay, the silica in a clay to be salt-glazed, etc., but it gives little or no information on the behaviour of a clay in the manufacture of ordinary goods.

Impurities in Clays

Assuming that 'pure clay' is composed of alumina, silica, and water in the proportions in which these occur in kaolinite or in the purest china clays—viz. silica, 46·51 per cent.; alumina, 39·54 per cent.; water, 13·95 per cent.—an excess of any one or more of these ingredients and of any other materials present may be regarded as 'impurities,' though these may be necessary for the production of certain goods or in order that the 'clay' may

[1] Joseph Prestwich: *Geology, Chemical, Physical, and Stratigraphical*, vol. i, p. 28.

have certain properties. Thus iron oxide is an essential constituent of red-burning clays, and felspar or other fluxes are equally necessary in clays which it is desired to vitrify. Nevertheless, this assumption is convenient in so many ways, since the errors involved in employing it may usually be neglected, and all 'clays' may for most purposes be regarded as composed of a hypothetical 'true clay' and 'impurities.' In this sense the chief 'impurities' in clays are silica and alumina compounds other than 'clay'; iron compounds; lime, magnesia, soda, and potash (usually termed 'alkalies'), and compounds of all these oxides, water, carbonaceous matter, and various minerals which may be conveniently classified together without regard to their composition.

Silica in the form of quartz, tridymite, chalcedony, flint, or quartzite, may be present in clays in an uncombined state, or it may occur as a constituent of one or more minerals (silicates).

The chief effect of adding free silica to a plastic clay is to reduce its plasticity, shrinkage, tendency to warp and crack, the amount of water required to make it plastic, and the tensile and crushing strength, and to increase its porosity after firing. If the clay is very impure, the addition of free silica may also increase its refractoriness, but the opposite effect is produced with a clay relatively free from fluxes, though the ability of the latter clay to withstand sudden changes of temperature may be increased.

Silica is largely used for the prevention or reduction of shrinkage, and is added in the form of sand or crushed rock to bricks, tiles, and coarse pottery, and as ground flint to white ware.

The addition of silica to a clay will raise the fusing-point of a clay if the latter is rich in fluxes (lime, magnesia, and alkalies), but it may have no influence on, or may even spoil, a refractory clay.

Alumina (Al_2O_3), like silica, occurs naturally in all clays: (*a*) in combination as an essential constituent, (*b*) in combination as an 'impurity,' and (*c*) in the free state. Free alumina is, however, seldom observed in raw clays, though according to Van Binimeler it occurs in many of them in the form of *laterite* or *hydrargillite* ($Al_2O_3.3H_2O$), both of which are decomposition products of diorites and granites. Alumina is also produced by heating clays to redness.

Alumina behaves sometimes as a base and sometimes as an acid. In clays its action is apparently neutral, so far as it is a constituent of the clay molecules and not as an 'impurity.'

In the form in which it exists in relatively pure clays—as a

hydrated aluminium silicate or an alumino-silicic acid—alumina may be considered to be the chief refractory oxide: indeed pure alumina is practically impossible.

The other chief compounds of alumina occurring in clays are *felspar* and *mica*. Their effect on refractory clays is to increase their fusibility, but with others they merely reduce the plasticity. The effect of adding free alumina (either artificially prepared or in the form of native *bauxite*) to a clay is similar to that of adding free silica, but a somewhat more refractory material is produced, and clays rich in alumina are apparently more viscous, and so retain their shape well when heated to the softening-point.

Iron Compounds. The chief compounds of iron occurring in clays are the two oxides (see Chapter III, Section II) (more or less hydrated), the carbonate, sulphide, and various minerals containing iron as an essential constituent, such as glauconite, ilmenite, etc. They are obtained from decomposed ferruginous rocks, either by direct admixture or by their becoming dissolved by organic acids, and the solution penetrating into the clay and being decomposed later.

Very few clays are quite free from iron compounds, and in buff and red-burning clays iron is essential to the production of the colour. Thus a clay with more than 4 per cent. of ferric oxide will usually burn red, with 3 to 4 per cent. it will be more brown or even purple, and with less than 3 per cent. it will usually burn white or buff. The colour is not closely proportionate to the amount of iron oxide present, but depends on the size of the particles and whether lime compounds are also present.

Iron pyrites is a not uncommon accidental product present in clays, and unless separated, durable, to say nothing of well-coloured, brick can never be made of the clay. The pyrites is but partially decomposed in the kiln; oxide of iron and basic sulphides of iron remain. When these are exposed later on to air and moisture, which are absorbed to all depths in brick, oxidation takes place, sulphate of iron, and frequently also sulphates of lime or alums (sulphates with double bases), are formed, and, crystallising within the mass of the brick, split it to pieces.

Lime Compounds, if in a very finely divided state (as chalk), are not injurious to clays used for brick-making, but coarser particles must be avoided, as they cause disintegration later. Marls (which are rich in lime compounds) are much used for brick-making, but boulder-clay (in which the limestone is in a coarse state) is less satisfactory, as the limestone cannot be ground sufficiently fine.

If the lime compounds are in the form of chalk and very evenly distributed throughout the mass, they will combine with any iron oxide and some free silica in the clay, destroying the red colour normally produced by iron and yielding a buff or whitish article (see Malms under 'Varieties of Clays' below). Hence it is impossible to produce a good red brick from a clay containing much lime.

Clays containing lime compounds fuse more readily and become impervious (vitrified) at a lower temperature than others.

Lime compounds diminish the plasticity of clays to which they are added, but to a less extent than silica.

Magnesium Compounds are of rather less importance than lime compounds in clays. They are derived in a similar manner from the destruction of magnesian rocks, and in many ways act like the corresponding compounds of lime, except that, when added to clays, magnesia acts much more slowly than lime, and consequently a high degree of vitrification can be secured in a clay with less risk of loss of shape than when lime compounds are used.

Titanium Compounds occur more frequently in clays than is commonly supposed, though only in small quantities, as they are usually included in an analysis in the figures for alumina. They occur chiefly as *rutile* (TiO_2), *ilmenite* ($TiFeO_3$), and *titanite* ($CaTiO_3$), and act as somewhat powerful fluxes; hence clays which are required to be highly refractory should not contain more than 2 per cent.

Alkalies (potash and soda compounds) are the most powerful fluxes known. Their effect is (*a*) to increase the fusibility; (*b*) to produce a scum on the surface of the goods; and (*c*) to diminish the plasticity of the clay when it is made into a paste with water.

Alkalies, when existing in clay to any great extent, are detrimental to its use as a material for brick-making, as their action as a flux causes the clay to melt and become useless.

Common *salt* is nearly always present in minute quantity in clays, but when these are taken from the seashore, from beneath the sea-washes, or from localities in and about the salt formations (Trias), they frequently, though in all other respects excellent clays, are unfit for burning into good brick. Chloride of sodium is not only a powerful flux when mixed even in very small proportion in clays, but possesses the property of being volatilised by the heat of the brick-kiln, and in that condition it carries with it, in a volatile state, various metallic compounds, as those of iron, which exist in nearly all clays, and also act as fluxes. The result is that bricks made of

such clays tend to fuse, to warp, twist, and agglutinate together upon the surfaces long before they have been exposed to a sufficient or sufficiently prolonged heat to burn them to the core into good hard brick. 'Place bricks' can be made of such clay, but nothing more; and these are always bad, because never afterwards free from hygrometric moisture.

A large proportion of **carbonaceous** or **organic** matter in an open brick earth is an advantage, as it reduces the amount of fuel required to burn the bricks, but much carbonaceous matter naturally mixed in clays is also in certain states objectionable, for when not burnt completely and in the kiln, which is sometimes difficult with the denser clays, the bricks are of a different colour in the exterior and interior, and will not bear cutting for face-work without spoiling the appearance of the brick-work. But, worse than this, such bricks, when wetted in the wall, occasionally pass out soluble compounds like those absorbed from soot by the bricks of the flue, and like these (when used again in new work) discolour plastering or stucco-work.

Water occurs in three forms in clay, viz.:

(*a*) as moisture or dampness;
(*b*) as water of formation, or that which is added to produce a workable paste;
(*c*) combined water.

(*a*) The *moisture* in a clay is sometimes troublesome, as it may produce a sticky adhesive material which is difficult to manipulate, and must therefore be dried or mixed with some absorptive, such as grog, very dry clay, or sand. Usually when the clay has been made into bricks, tiles, pottery, etc., the moisture becomes part of the 'water of formation,' but it is in the grinding of the clay where the presence of moisture *per se* is apt to be troublesome.

Clay is naturally hygroscopic, and when fully dried and then exposed to the air it rapidly absorbs moisture from the latter, even though it may not become actually wet.

(*b*) *Water of formation.* Water is added to clay for a definite purpose, viz. to make it of convenient consistency and plasticity, and cannot, unless it be present in excess, be regarded as an impurity. Any excess of water may usually be removed by exposing the clay to the atmosphere, or, more rapidly, to a current of warm air.

In the manufacture of articles it will be found that each kind of clay requires a definite proportion of water for its efficient manipula-

tion. If more is added it will become too weak; if less it will be too short. The amount of water needed for the purpose is less in proportion as the ratio of non-plastic material in the body increases. Therefore the leaner the clay, the less water it will need to temper it.

(*c*) *Combined water.* All clays contain an amount of combined water roughly proportional to the true clay and other hydro-alumino-silicates present, which cannot be removed without heating the clay to redness. This combined water is an integral part of the clay molecule, and is represented by $2H_2O$ in the formula for kaolin ($Al_2O_3 2SiO_2.2H_2O$). It is only expelled at a temperature of 400° to 600° C., and is accompanied by a slight shrinkage; the clay then loses its plasticity, and cannot recover it by any treatment yet devised, but becomes hard and stony.

The combined water is essential; the plasticity of the clay depends upon it, and it cannot in any sense be regarded as an impurity.

Effects of Heat on Clay

In the heating of a clay four distinct stages may be quoted, each one overlapping the others to some extent. These four stages are termed:

1. **Baking**, or heating until the clay particles have lost their plasticity and have formed a moderately hard mass composed of particles adhering together, the mass remaining porous. Fire-bricks, the softer varieties of building bricks, such as 'rubbers,' and 'biscuit-ware' are of this type. The end of this stage is sometimes termed the *point of incipient vitrification*, or the *sintering-point.*

2. **Vitrifying**, or heating the mass until some of the ingredients have melted and have partially or completely closed the pores, as in stoneware and porcelain. The completion of this stage occurs at the point of maximum shrinkage without loss of shape. The vitrification will continue until the whole mass is fused, if the heat be sufficient; but if (as is usually the case) the shape of the material is important, the end of the vitrification stage of firing may be taken as stated.

3. **Squatting** or **Softening**, which occurs when so much of the material has fused that the mass begins to lose its shape and becomes viscous.

The temperature difference at which these changes occur vary with each clay; thus a clay rich in magnesia may be far more completely vitrified without losing shape than another clay containing the equivalent proportion of lime. Hence the influence of

impurities in clay is often most powerful when the latter is heated to the temperature of vitrification of the mixture.

4. **Fusion** occurs if the material is changed from the solid to the liquid state, but complete liquefaction takes place so gradually with most clays that a 'fusion-range' and not a 'fusion-point' is obtained.

Fusion may commence at a temperature of only 500° C., but may be incomplete after the material has been heated to a temperature of 1200° C., though the amount of fused substance has increased all the time.

A reaction commences between the alkalies and the siliceous matter in the clay, then the lime enters into combination, and is rapidly followed by the iron. The finer particles of fusible minerals next fuse, and as the volume of fluid increases with a rise in temperature, it attacks the clay particles, then the coarser quartz, felspar, etc., until only the largest particles of the most heat-resisting materials are left. In the manufacture of articles from clay there must always be left a sufficient 'skeleton' of unattacked material to enable the shape of the article to be retained.

The **fusibility** of a clay is a characteristic which is seldom studied, as the temperatures at which most clays fuse are so extremely high as to be almost unattainable. What is usually termed the 'fusibility' of a clay is really the temperature at which sufficient of its ingredients have fused to cause the whole mass to lose its shape. This is really the softening temperature.

It is more usual to refer to the 'refractoriness' of clay than to its fusibility.

Contraction. Two sets of forces, then, are or may be in play in the burning of brick—chemical, and physical or molecular—and must be held in view by the scientific brick-maker. To the latter belongs the contraction that takes place in the process of firing of all porcelain and brick. This is greatest with those which contain most alumina, and with any given specimen is great not only in proportion to the elevation of the temperature to which it is exposed, but with the duration of the time of exposure. It is least in compounds in which the silicic acid predominates; and if these pass partially from the crystalline to the vitreous state of aggregation in the firing, the specific gravity is reduced and the increase of volume may more than equal the contraction. This is said to be the case with Dinas firebrick, which, when highly heated in furnaces built of it, is said to expand.

Colour. There is little or no connection between the colour of a raw clay and that after firing, and the effect of heat on colour can seldom be predicted with certainty. Thus, although clays low in iron usually burn white or buff, and those with 5 per cent. or more of iron generally become red or burn on heating, this is by no means always the case. A clay containing both iron and lime compounds will, at a low heat, burn red owing to the iron oxide present, but at a higher temperature the lime will unite with the iron to form a yellowish or cream-coloured silicate of iron and lime. For this reason red-burning clays are mixed with chalk to make 'white' bricks. The conditions of heating also affect the colour; thus, certain clays containing iron compounds will burn red in an oxidising atmosphere, but in the presence of carbon and a limited supply of air a black or 'blue' colour will result, the difference being due to the formation of less highly oxidised iron compounds, owing to the reducing atmosphere employed.

Varieties of Clays

China Clay or kaolin is the purest form of clay known, and on analysis yields almost exclusively alumina silica and water—the 'impurities' in first-class china clays not exceeding 5 per cent. China clays are less plastic than the common or plastic clays, and generally burn to a white porous mass; but even the less pure forms are valued on account of their refractory nature. China clay is soft to the touch and has a soapy feel, that from Cornwall being more unctuous than clays from other parts of Europe. If cut smooth and rubbed with a piece of smooth bone it will take a beautiful polish.

China clay is found in china clay rock (see above), and also in pockets of relatively pure clay. In both cases it forms a yellowish-white mass, usually containing crystals of quartz and undecomposed granite, and numerous lamellar particles of mica.

Ball Clay, which occurs as a stiff plastic mass, very difficult to dig, is cut into rectangular or cubic blocks or 'balls' weighing about 36 lb. each, and measuring about 9 inches by 6 inches by 5 inches. It is from these that the ball clays derive their name.

Ball clays are remarkably plastic, and contain so little iron that they are largely used for the manufacture of white ware. Before firing they are dark-coloured—sometimes approaching black, owing partly to the organic matter they contain, which probably has some connection with their extraordinary degree of plasticity. They

often contain 3 or 4 per cent., or even a larger proportion of carbon in the form of lignite or other organic matter, chiefly of vegetable origin. In chemical composition the ball clays do not differ greatly from the china clays, except that they often contain a rather larger proportion of alumina and iron, are more vitreous when fired, but do not burn so white as the china clays. They are found away from the granitic rocks, from which they are supposed to have been primarily derived, and have in the course of their travels been so treated that they have gained enormously in plasticity without any noticeable change in composition.

Ball clays are largely used by potters to produce a plastic and easily worked body. They are really the foundation of most pottery, other clays and non-plastic materials being added to correct any excessive shrinkage or other defects in the ball clay, or to give the mixture special properties.

Pipeclay was originally any clay suitable for making tobacco-pipes, but the term is now used to include all white-burning clays of considerable plasticity. Thus the ball clays form one end of a series, with pipeclay as the central member and china clay as the further end.

Ochre and **Bole** are clayey earths furnishing pigments.

Adobe Clay is similar to ' loess,' and is a silt mixed with coarser calcareous matter. It is chiefly found in countries in which streams occur which are usually rapid, but which periodically slacken speed and so carry off only the clay and a few heavier particles to other places.

Grog is burned clay. It is used to reduce the shrinkage of plastic clays and to give additional porosity. It enables refractory goods to withstand sudden changes of temperature, and has an advantage over sand and other forms of silica in that it does not swell when heated.

The use of a large quantity of grog in a clay mixture also reduces the proportion of alkalies present, as these are partially volatilised during the preparation of the grog. Hence this forms a convenient method of slightly raising the heat-resisting power of a clay.

Grog is often obtained by grinding old firebricks, but the best qualities are made by burning a high-grade fireclay in a shaft kiln out of contact with fuel, grinding the product to a coarse powder, and removing the dust by screens with twelve or sixteen holes per linear inch.

Chamotte is the foreign equivalent of grog.

Laterite Clays (see Chapter VIII, Section I) are those which are presumed to have been chiefly formed in tropical areas or under tropical conditions by a process of exposure or 'weathering,' which results in the production of a material containing free alumina as well as free silica. The manner in which this special form of weathering occurs and the agencies which effect it are not known, though it is understood that laterisation is a kind of 'continuation effect' whereby ordinary clays under tropical conditions are partially decomposed into free alumina and silica, forming laterites.

The characteristic features of laterite clays are their peculiar red colour—though some grey ones are known—and the large percentage of free alumina they contain.

Loess is a German term, also used by American clay-workers, for a peculiar light yellow or yellowish-grey marly loam of fluviatile or æolian origin (see Chapter I, Section I). It also occurs as a quartz-sand of a dirty yellowish-brown colour, mixed with a small quantity of clay and sometimes also containing chalk or limestone. Loess is not truly plastic. It contains numerous calcareous concretions, which sometimes take curious shapes, and are known on the Continent as 'loess-men.'

It also has a characteristic porous structure which renders it easy to recognise.

Marls are natural mixtures of clay and chalk—the latter being in a finely divided condition—but the term 'marl' is often used to describe a friable or crumbly earth in order to distinguish it from plastic clay and from the harder shales. This use of the word 'marl' is distinctly confusing, though very common, particularly in connection with the Staffordshire deposits used for making blue bricks.

Unless distinguished by some adjective, the term 'marl' may be understood as referring to a clay made impure with chalk or extremely fine limestone, which often has a greenish or yellowish-brown tint, owing to the presence of iron oxide. If bituminous matter is present the material is dark in colour. When exposed to the air it breaks up and falls to a mass of irregular pieces, or even to powder.

Marls are classified according to the percentage of lime and clay as (1) chalk marls, and (2) clay marls, but no definite figures have yet been agreed upon as to the limit of composition for each class.

The term 'marl' is not used for clays containing less than 10 per cent. of chalk, *i.e.* for those which do not effervesce violently on the addition of hydrochloric acid.

For ordinary malm bricks as much as 25 per cent. of chalk may be present in a clay, but for bricks and tiles intended to resist the action of the weather 12 per cent. is the most usually permissible, though much depends on the nature of the other ingredients.

The plasticity of marls depends on the proportion of silica and alumina so that, generally speaking, clayey marls may be considered as plastic substances, but calcareous marls as lean and friable ones, without much coherence, though usually sticky when wet.

Marl is markedly lighter in weight than clay.

Sagger marls are really fireclays of second quality, but sufficiently refractory to be used in the production of saggers or cases to protect the goods whilst in the kiln.

Malms are clays containing, in the natural state, a considerable proportion of chalk, and may often be made into bricks without any admixture; but as clays containing exactly the proper proportions of clay and chalk are somewhat scarce, it is usual to prepare artificial malms by adding chalk to clays otherwise suitable. The object of the chalk is threefold: in the first place, it acts mechanically in diminishing the contraction of the clay during the drying and burning; secondly, it acts chemically as a flux during the burning, combining with the silica of the clay so that a much harder and more durable material is produced; and thirdly, it produces bricks of a pleasant whitish or buff colour, due to the combination of the lime with any iron compounds in the clay.

Loam is a term used to describe any soil which is neither distinctly sandy nor clayey in texture. It comprises the light, open soil produced by the decay of leaves and other vegetable matter, and also mixtures of sand and clay. Agriculturists speak of light and heavy loams according to the proportion of clay present; also of sandy and calcareous loams according as sand or chalk is a predominating constituent.

Some writers appear to confuse loams with *marls*. In loams, there should not be sufficient limestone or chalk to make either of these substances characteristic of the material. Broadly, the distinction between them is that loams are sandy clays whilst marls are calcareous ones.

In the sense in which the word is used by brick-makers, loam is intermediate between the plastic clays, which shrink too much to be used alone, and the sands, which cannot be moulded into bricks without the aid of powerful machinery.

Shale. Clayey rocks which split into layers along planes of bedding are called *shale*; *bind*, *blue-bind*, *plate*, *shiver* are other names applied by miners to the same rock. Shales containing a sufficient quantity of iron pyrites are used for the manufacture of alum, and are called *alum shales*. When there is a good deal of sand present, the rock is called *arenaceous* or *sandy shale*, or *stone-bind* or *rock-bind*. These forms pass gradually into argillaceous sandstones and common sandstone. Shales stained dark by vegetable matter are called *carbonaceous shale*, *bass*, or *batt*. When such shales contain sufficient bituminous matter to be used for the manufacture of paraffin, they are called *oil shales*. Such shales pass gradually into cannel coal occasionally. The streak of oil shales is usually brown.

Clunch is a term largely used to indicate any clay which is mined and not quarried, and particularly certain shales and fireclays found near coal seams. The 'clunches' vary greatly in composition, and some of them are far too impure to be used for anything better than common bricks; others are good for firebricks and other refractory goods. The better qualities of clunch are identical with fireclays, and can only be obtained by carefully selecting the material in the pit. Inferior qualities may be regarded as brickmaking shales. '*Stone clunch*' is another name for gannister (see under 'Refractory Materials' below).

Flaky Clays are intermediate between fat clays and shales. When crushed, they form flakes which will not easily unite to form a uniform plastic mass unless this is made too soft to be convenient. They must be so treated that the flakes are destroyed, or the clays cannot be used.

Flint Clays are usually refractory, but they derive their name from their intense strong (flint-like) hardness, their conchoidal fracture, and their general structure, which is not unlike that of flint. When fairly pure they are added to excessively plastic clays to reduce the plasticity of the latter, though they are costly to grind.

Fuller's Earth is a term used for any earthy material which will act as a grease absorbent, and may be employed for fulling wool. Fuller's-earth is also used for decolorising oils, particularly cottonseed oil, lard oil, castor and coco-nut oils, and in the manufacture of some soaps.

The term is usually applied to certain white marls and oolite clays, but some varieties of china clay are also used for this purpose.

Brick and Tile Clays

Distribution. Brick and tile clays are widely diffused. The thickest and most extensive beds are the so-called ' brick clays ' of the Glacial or immediately post-Glacial period, and which are generally fine in texture, and red, blue, yellow, or grey, according to the rock formations from which they have been derived or with which they are associated; but abundant supplies can also be obtained from estuary silts, from the clays of the Tertiary system, and occasionally from the outcrops of the argillaceous beds of the older systems.

Brick Clay. This term, though used by some geologists in contradistinction to ' boulder-clay,' should more correctly be used to include all clays capable of being used commercially to produce bricks.

Owing, however, to the large proportion of material other than clay usually present in so-called ' brick clays,' it is generally preferable to use the term ' brick earth.'

Brick Earth is any material of an earthy nature suitable for making bricks. The term is often confined to certain superficial deposits in the London basin, but may be conveniently extended to include all materials used for brick-making, with the possible exception of unmined shales and rocks. In this wider meaning the term ' brick earth ' includes the following :—

1. Plastic clays.
2. Loams or sandy clay.
3. Marls or calcareous clay.
4. Vitrifiable clays (for engineering bricks).
5. Fireclays (for firebricks).
6. Silica rocks (for silica bricks).

The two last-named may, however, be excluded as being ' rocks ' rather than ' earths.'

Most brick earths consist of an irregular mixture of pure clay with sand and other minerals. Pure clays, especially when highly plastic, are not suitable for brick-making unless mixed with appropriate non-plastic material.

No definite composition can be stated as truly representative of brick clays, as the amount of shrinkage on drying and burning is often more important than the chemical composition of the earth.

Any plastic earth in which the total shrinkage does not exceed 10 per cent. is worth investigation as to its suitability for brick-making, and particularly so if its composition approximates to silica, three-fifths; alumina, one-fifth; iron, lime, magnesia, manganese, soda, potash, and 'loss on ignition,' one-fifth. Such a composition corresponds to 50 per cent. true clay (Kaolinite, see 'Origin of Clays' above), and this should form the chief constituent of brick earths.

The effect of 'impurities' in clays is described above.

A good brick earth should contain, in itself, sufficient flux to fuse some of its constituents at the temperature attainable in the kiln, but not so much as to make the bricks run together and become vitrified.

It frequently happens that a clay, as found in Nature, is unfit for brick-making purposes; it will probably be found that it is deficient in some necessary quality, and this has to be supplied by mixing it with other clays, or by adding the constituent lacking, such as sand, lime, or burned clay. The amount of this addition must be found by actual trial.

Occasionally the different beds in a clay-pit vary so much that it requires a mixture of two or three different beds before an earth suitable for brick-making is obtainable.

Roofing-tile Clays are similar in character to those used for making the better qualities of hand-made bricks, and must possess a good red colour when burned. They must be sufficiently plastic to be used for the manufacture of thin slabs or sheets, and yet must not shrink sufficiently to cause warping and cracking in the kilns.

The chief requirements and characteristics of a clay for roofing-tile manufacture are that it shall be highly plastic without being 'sticky'; it must be sufficiently refractory to give a tile having great durability, yet should contain enough vitrifiable matter to produce tiles having a good 'ring' without being too dense.

Brick-making

While engineers in Great Britain and most civilised countries have no difficulty in procuring such bricks as they require from manufacturers using up-to-date machinery, engineers in various parts of the Empire and elsewhere often have to arrange for the manufacture of their own bricks. The first requisite is to ascertain whether a suitable brick earth is obtainable anywhere in the district where the engineer is working.

Choice of Clay. The different varieties of clays, etc., which come under the head of 'Brick Earths' are referred to under 'Brick and Tile Clays' above.

Chemical Composition. There are two distinct types of clays or brick earths: (1) Clays or shales which consist chiefly of hydrated aluminium silicates (known as *clay substance*), with a small proportion of carbonate of lime; (2) marls containing a considerable percentage of carbonate of lime, *e.g.* as much as 40 per cent. of chalk.

All clays contain more or less silica in the form of sand, and, in addition to the clay substance and sand, the presence of oxide of iron, which gives colour, hardness, and durability.

Practical Test. While a chemical analysis will be of some use in giving an idea as to the suitability of a sample of clay, a practical test, such as can be made by a professional clay-worker, will be of more use to the engineer. He can generally tell whether the clay is suitable by moistening a small sample, kneading it and rubbing it between the thumb and forefinger, and then firing it.

'Potters' are to be found in many places, and tile-makers are not uncommon. Such men can be very useful in the choice of a clay for brick-making, and their advice may be of assistance in deciding whether more sand or more tough clay should be added, as is often necessary.

Supply of Clay. Clays should, if possible, be delivered into the brickyard in their moist, natural state, for when they have been permitted to dry up under a scorching sun or drying wind, they shrink and harden greatly, and the labour of mixing into good brick 'stuff' is greater, and the plastic mixture not so free and nice as before.

Uniformity or Homogeneity. It is essential that the clay should be uniform in composition, and to obtain this result the clay should first be weathered, then purified by washing, etc., and finally tempered, or mixed with water. It is often necessary to grind the clay and to 'sour' or 'age' it.

Weathering consists of exposing the clay to the action of the weather, especially in the colder months, in order to break up the clay into minute particles and thus render it easier to mix with water and to be worked.

Many clays break up on exposure to the air within forty-eight hours or so; others require the action of water or frost. In all cases the clay should be spread out, so as to expose as large a surface as possible to the weathering process.

Purifying consists of washing or screening out gravel, small stones, or other foreign matter.

Tempering consists of mixing with water and reducing the clay to a plastic condition. It may be carried out by mixing with spades, with the hands or the feet, or by means of a pug-mill or a pan-mill.

Brick-burning. For description of kilns, methods of burning, fuel, etc., the engineer is referred to technical books, with the proviso that, when undertaking the manufacture of bricks in remote parts, it is desirable to adopt the best local methods and improve on them by building better kilns, using better fuel, being more careful in stacking the unburnt bricks in the kiln, etc., etc.

Refractory Materials

These include (*a*) materials resistant to heat in the presence of air, and (*b*) those which resist direct chemical action.

They may be (1) *acid*, *e.g.* fireclays and siliceous materials; (2) *neutral*, *e.g.* graphite, chromite, etc.; (3) *basic*, *e.g.* lime, magnesia, bauxite, zirconia, etc. Acid substances should not be used in basic vessels, etc., and *vice versa*.

Fireclay. The term 'fireclay' is commonly used for any refractory clay, but in England fireclays are found chiefly in the Coal Measures, and consist of (1) shales, and (2) underclays. The latter lie immediately beneath the coal, and are usually more refractory than the shales.

Bastard fireclays are underclays which have not enough refractoriness for firebricks, but are used for building bricks and salt-glazed ware.

Fireclays vary greatly in composition, even from the same seam. They are all alumino-salicic acids with more silica than kaolin, and contain various other minerals. To judge of their suitability for firebricks, the best way is to make a test brick and subject it to the heat which it is required to stand.

Siliceous materials used for firebricks and other refractory articles contain from 75 to 99 per cent. of silica, and comprise:

(1) *Silica rocks*, chiefly quartz or quartzite, e.g. *Dinas rock*, which may contain 90 per cent. of silica.

(2) *Siliceous fireclays*, mainly fine white clay mixed with clean sharp sand, found in pockets.

(3) *Firestones* are porous siliceous rocks which can resist a high degree of heat. They are used in place of low-grade firebricks.

(4) *White sands* are usually quartzitic, and must be pure enough to resist heat and slags. They are used for the final layer in Siemen's steel furnaces.

(5) *Gannister* is a slightly plastic, fine siliceous grit, containing up to 10 per cent. of clay, which occurs in the Coal Measures. The value as a refractory material lies in close-fitting angular grains and colloidal cement. It is used as a lining for furnaces.

Floating bricks are made of diatomaceous, infusorial, and microphytal siliceous earths, mixed with a paste of lime and clay. They are only one-sixth the weight of ordinary bricks, and are used for fireproofs on board ship.

Terra-cottas are unglazed ware, prepared from the finest fireclays.

BIBLIOGRAPHY

(In addition to works quoted)

MELLON, J. W.: *Clay and Pottery Industries.*
SEARLE, A. B.: *The Clayworker's Handbook.*
,, ,, : *British Clays, Shales, and Sands.*
,, ,, : *Refractory Materials.*

CHAPTER X

LIMES, CEMENTS, AND PLASTERS

Portland cement is so largely used in Great Britain by the engineer and builder that, except in rare cases, lime mortar is seldom taken into account for any purpose other than plastering. But, to those employed on works of construction overseas, where the cost of Portland cement is often prohibitive, a knowledge of the uses of the various kinds of lime, and of the distribution and nature of the limestones from which they are derivable, is of the highest importance. Especially is this the case where the ordinary lime of the neighbourhood is a 'fat' lime, as by a proper admixture of suitable substances the engineer may greatly add to its hydraulicity.

DEFINITIONS

Hydraulicity. Limes and cements which possess the power of setting or solidifying under water are said to be *hydraulic*. This power is due to the presence of alumina with the lime. The admixture of alumina and lime may be natural, as in the case of *Blue Lias lime* and *Roman cement*, or artificial, as in the case of *Portland cement*.

The **Lime** used for building purposes is produced by calcining calcium carbonate ($CaCO_3$) in the form of limestone, marble, chalk, sea-shells, etc., and thus drawing off the carbonic acid (CO_2). The result is an anhydrous calcium oxide (CaO) called *quicklime*, which is a white powdery material.

When water is added to quicklime it is said to be *slaked*. Quicklime also readily absorbs moisture from the air, and becomes air-slaked.

Cement. In the building world cement, *e.g.* cement-concrete, cement rendering, neat cement, etc., always means **Portland cement.** In the latest edition of the *Encyclopædia Britannica* the term 'lime cement' is used to denote what builders call 'lime.'

Redgrave and Spackman describe cements, as distinguished from limes, as 'materials which are capable of solidifying when in contact with water, without perceptible change of volume or

notable evolution of heat,' while limes, 'as distinguished from cements, "fall" or crumble when exposed to the action of water.'

But some hydraulic limes would come under the former definition, and it appears preferable to distinguish cements from limes by the necessity for calcination to the point of total or partial vitrification and for subsequent grinding.

Intermediate Limes. 'Certain impure limes, resembling in their composition the constitution of cements, have been appropriately named "intermediate limes," or such as occupy a position intermediate between the true limes, which undergo disruption when exposed to the action of water, and the cements which do not, apparently, become changed when so treated.

'It may be assumed that limes of every different degree of energy, from pure oxide of calcium down to true calcareous cements, exist in nature; thus there is an enormous range of varieties of action to be studied, and any attempt to classify all limes under two or three sub-heads must be futile and untrustworthy.' [1]

Limes

Classification of Limes. Some writers have attempted to classify the different varieties of lime in accordance with the quantity of slaked lime produced, or with the speed with which they were observed to combine with water. For instance, limes are frequently classed as *fat* or *rich* limes if they readily become slaked and furnish a large volume of powder, and *poor* if they are impure and become slaked slowly, yielding relatively but little dust; or, when falling rapidly to quicklime, they are *rich*; when falling only after eight or ten minutes, they are *poor*; when they require fifteen or twenty minutes, they are *medium*; when requiring an hour or more, they are regarded as *hydraulic*; and when requiring, it may be, several days to break up, they are *highly* or *energetically hydraulic*.

It is, however, now known that this slaking action depends upon numerous conditions which have to be specially studied for each class of limes, and that any general deductions founded on the act of hydration alone are likely to be inaccurate and misleading.

The old classification into fat, poor, medium, hydraulic, and eminently hydraulic limes is still met with in many engineering books, and as a rough guide is of considerable value if due caution is observed.

[1] Redgrave and Spackman: *Calcareous Cements*. 2nd ed.

Combination of Lime with Water. 'The chemical affinity of lime for water is one of the most powerful with which we are acquainted, and "quicklime" (calcium oxide), or lime recently calcined, when exposed to the air, speedily attracts moisture from the atmosphere, and combines with such water to form calcium hydroxide, or slaked lime. This hydroxide may occupy as much as three times the space previously filled by the quicklime, and therefore the amount of slaked lime produced from a given bulk of quicklime appears in certain cases to be very considerable.' [1]

'The water which combines with the lime in the act of hydration is truly solidified, and the hydrate formed is, when the exact proportion of water necessary for this purpose has been employed, an absolutely dry powder. On adding a further quantity of water, the bulk of this powder is much reduced, and it may be tempered into an extremely rich and unctuous paste. If this paste is permitted to dry, it shrinks and forms a porous mass of no great hardness.' [2]

Quicklime. 'Quicklime, caustic lime, or the oxide of calcium, one of the earthy metals, does not exist in Nature, nor is metallic calcium itself anywhere found in an uncombined form. We obtain quicklime, the chemical symbol for which is CaO, by calcining or heating to redness a carbonate of lime, $CaCO_3$, and by this means expelling the carbonic acid gas or carbon dioxide, CO_2, with which the lime is combined, and which can be driven off in the gaseous form at a cherry-red heat (about 440° Centigrade),' [3] calcination being complete when the mass has attained a white glow. If prolonged beyond this point the lime will be overburnt and will blow when setting, as it is very difficult to slake.

'Lime combined with carbonic acid is found in a great variety of rocks in all parts of the world, and in every different degree of purity (see *Limestones* below).

'In a pure carbonate of lime 44 parts by weight of carbon dioxide or carbonic acid are combined with 56 parts by weight of calcium oxide. In the oxide itself 40 parts by weight of metallic calcium, Ca, are combined with 16 parts of oxygen gas, O. This oxide cannot be decomposed by heat.

[1] Redgrave and Spackman: *Calcareous Cements*, 2nd ed., p. 2.
[2] Redgrave and Spackman: *Ibid.*, 2nd ed., p. 4.
[3] Redgrave and Spackman: *Ibid.*, 2nd ed., pp. 2–3.

'*Calcination.* Generally speaking, the limestone or chalk, when placed in the kiln, contains a certain percentage of moisture which has also to be expelled, and thus the lime-burner can rarely, when the stone is thoroughly well burned and all the carbon dioxide is expelled, obtain more than half its weight of quicklime from a given weight of stone dealt with in the kiln, though in theory the yield should be 56 per cent. of lime.'[1]

Slaked Lime. 'When lime becomes "slaked" it is found that 56 parts by weight of quicklime combine with 18 parts by weight of water, H_2O, to form 74 parts of calcium hydroxide, $Ca(OH)_2$. Great heat is evolved in this process, and the action is expedited by the use of boiling water. Certain "poor limes," which will scarcely slake or fall to powder when cold water is employed, will crumble into dust readily if the water is at the boiling point.'[2]

Lime slowly recombines with Carbonic Acid. 'When exposed to the air, pure caustic lime is converted very slowly and without notable increase of temperature into a rather coarse powder. It is not, under these circumstances, wholly converted into a carbonate of lime, even after the lapse of many years, but, by the simultaneous absorption of moisture and carbonic acid, it is resolved into a double compound having the formula, according to Fuchs, of $CaCO_3 + Ca(OH)_2$, or consisting of equal equivalents of the carbonate and the hydrate of lime. The carbonate thus produced would seem to result from the decomposition of the first-formed hydrate, for when moisture is wholly excluded no combination between the lime and the dry carbonic acid gas takes place. In order to expel the water of hydration, the slaked lime must again be heated to dull redness.'[3]

$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$ on evaporation; the H_2O then dissolving another particle and putting it into condition to combine with CO_2 again, and so on.

'*The action of carbonic acid mainly superficial.* Lime made from pure carbonate of lime, when slaked and used for mortar, likewise gradually recombines with the carbonic acid gas present in the atmosphere and becomes indurated, but this action is mainly in the superficial layers of the mortar, as the gas penetrates very slowly. In fact, years must elapse before the recarbonisation

[1] Redgrave and Spackman: *Calcareous Cements*, 2nd ed., pp. 2–3.
[2] Redgrave and Spackman: *Ibid.*, 2nd ed., p. 4.
[3] Redgrave and Spackman: *Ibid.*, 2nd ed., p. 5.

of the lime is thoroughly accomplished, and in the case of thick walls the internal layers of mortar never become completely hard. It is necessary to distinguish between the so-called "set" of the mortar, which is merely due to the absorption of the superabundant water, and the actual induration by means of the carbonic acid gas which is a process of years, or of ages in the case of pure limes.' [1]

Hydraulic Limes

The Influence of Clayey Matters. 'Absolutely pure limestones are only met with in exceptional cases, as nearly all limestone rocks, and the greater part of the Chalk formation, contain varying percentages of clayey matters (silicates of alumina), iron, alkalies, etc., and it is upon the proportion of these ingredients present that the behaviour of the calcined lime principally depends. It is, in fact, owing to the presence of certain of these clayey matters that limes pass over by gradual stages into the form of cements; that is to say, that these substances so far influence the slaking action that they may even bring about the ultimate setting of the mixture without change of volume—the characteristic property (as already stated) of cements.' [1] A test for which property cement should always be subjected to.

Artificial Admixture of Clayey Matters. 'It is not necessary, however, that the limestone should have been the source from which these clayey matters were derived; they may be conveyed to the calcined lime by admixture with it at the time when it is treated with water, or they may be ground up along with the lump lime before it is slaked. It is this fact which needs careful consideration when we have to deal with the influence of heat on mixtures of lime and clay, and the nature of the changes effected in the kiln. The silica compounds are of a very complex character, and may be produced, as we shall see, both by heat and in the humid way. All that is necessary for the due action of these clayey matters is that they should themselves have been roasted or calcined either artificially or by volcanic heat.' [2]

Pozzuolana, Trass, etc. 'Certain of these substances which are added to pure limes to bring about this action are called pozzuolanas or trass. These are clayey or siliceous matters of volcanic origin, but roasted shales, brick dust, and burnt clay or ballast, all of them,

[1] Redgrave and Spackman: *Calcareous Cements*, 2nd ed., p. 5.

[2] Redgrave and Spackman: *Ibid.*, 2nd ed., pp. 5–6.

more or less, possess this influence on the pure limes, and have the power of imparting to them the attributes of cements.' [1]

The cement used for burning the old Roman aqueducts was made of a mixture of pozzuolana, lime, and pounded brick or potsherd. The 'new trass' of the Danube has been well reported on.

'The volcanic ash found in the island of Santorin, and known as Santorin earth, is typical of many kinds of scoriæ which have been used successfully with fat or pure limes to impart to them hydraulic properties. The proportion of silicate of alumina in this substance is relatively high, and there is much less iron than in the case of trass and pozzuolana.' [1]

Surkhi or **Soorkee**, consisting of powdered brick or burnt clay, is largely used in India both as a substitute for sand in parts of the country such as Bengal where no sand exists, and as an addition to the lime to give it hydraulicity. When used as a substitute for sand it should be well burnt or even rather overburnt, hard and sharp, but when used to give hydraulicity it should be slightly underburnt in order to allow the alumina to combine with the lime. Balls of clay are often burnt and ground to form surkhi instead of reducing burnt brick to powder. Better results are obtainable with a disintegrator than by using the ordinary bullock-driven mortar mill for the purpose. The proportion of surkhi to be used in mortar varies in different districts according to the nature of the lime—the amount required being ascertained by experiment.

Influence of Heat on the Silicates. 'When limes, such as are combined with varying percentages of silicates, are burnt in the ordinary way in the kiln, the carbonic acid gas is first expelled from them, as in the case of the pure limestones, and the clayey matters assist in its expulsion, owing partly to the affinity of the silicic acid for the lime, and partly to the fact that the free and combined water in the clay is driven off, and the steam produced in this way facilitates the expulsion of the carbonic acid. There is thus a double change to be effected in the kiln, and the expulsion of the water from the hydrated silicate of alumina in the clay may go on side by side with the dispersal of the carbonic acid.

'These clayey limestones are thus burnt more readily than the pure limestones; they also require less fuel and less time.' [2]

[1] Redgrave and Spackman: *Calcareous Cements*, 2nd ed., p. 6.

[2] Redgrave and Spackman: *Ibid.*, 2nd ed., p. 7.

Limestones

Subdivisions. 'The minerals which contain the carbonate of lime and which are designated under the generic name of "limestones" or "calcareous stones" are of very various natures. They are mostly composed of carbonate of lime, of magnesia, of oxide of iron, of manganese, of silica, and of alumina, combined in variable proportions; and they are also found with a mechanical admixture of clay (either bituminous or not), of quartzose sand, and of numerous other substances. The name of limestone is more especially applied to such of the above mixtures as contain at least one-half of their weight of carbonate of lime. Mineralogists distinguish the subdivisions by the names of "argillaceous, magnesian, sandy, ferruginous, bituminous, fetid," etc. The subdivisions, again, are often characterised by varieties of form and contexture which are known specifically under the names of "lamellar, saccharoid, granular, compact, oolitic, chalky, pulverulent, pseudomorphic, concreted," etc., etc. (see Chapter V, Section II).

'This nomenclature is important, for every description of limestone yields a lime of different quality, distinct in colour and weight, in its avidity for water, and especially in the degree of hardness it is capable of assuming when made into mortar. But the physical and mechanical nature of a stone are far from being certain guides as to the quality of the lime it can yield. A chemical analysis of a hard sample also frequently gives different results from those obtained in practice. Experience alone should be the final guide of the engineer or of the builder.'[1]

Chemical Nature of Stones furnishing Different Sorts of Lime. 'A chemical examination of the stones which furnish the different limes of the old classification shows that:

'1. The pure calcareous rocks, or such as contain only from 1 to 6 per cent. of silica, alumina, magnesia, iron, etc., either separately or in combination, give *rich* limes upon being burnt.

'2. The limestones containing insoluble silica in the state of sand, magnesia, the oxides of iron and of manganese, in various respective proportions, but limited to between 15 to 30 per cent. of the whole mass, yield *poor* limes.

'3. The limestones containing silica in combination with alumina (common clay), magnesia, and traces of the oxides of iron and of

[1] G. R. Burnell: *Lines, Cements, Mortars, etc.*

manganese, in various respective proportions, but within the limits of from 8 to 12 per cent. of the whole mass, yield moderately hydraulic limes.

'4. When the above ingredients are present in the proportion of from 15 to 18 per cent., but the silica in its soluble form always predominating, the limestones yield a *hydraulic* lime.

'5. When the limestones contain more than 20 and up to 30 per cent. of the above ingredients, but with the soluble silica in the proportion of at least one-half of them, the limestones yield eminently hydraulic limes.' [1]

Calcination

Kilns and Fuel. The limestones, after being quarried and broken into moderate-sized pieces, are calcined, either in temporary or in continual kilns—that is, open kilns which are blown out till the calcined charge has been removed, or in draw-kilns, where the removal and charging proceed continuously. To avoid carriage, it is desirable to have the kilns as central as possible to the face of the quarries; and the longer the stone has been exposed to the air, the less fuel will it require to drive off the inherent moisture or quarry-water. The fuel employed in calcination is ordinary pit coal (1 ton to 4 or 5 tons of limestone), and in remote districts peat and brushwood; but for some sorts of limestone impure or shaly coals (while also much cheaper) are better adapted than the pure coals, as burning the stone more slowly and equally, as well as keeping it open and preventing slagging and sintering. More kiln-dust may be produced by the use of these slaty coals, but fewer cores and slags will be found among the lime.

When properly burnt—that is, when not slagged or covered with a siliceous glaze by too sudden ignition—the limestone loses its carbonic acid, and is converted into caustic- or quick-lime.

Admixture with Ashes. 'For many purposes for which lime is used commercially, it is very important that it should be as pure as possible, and free from the ash or clinker arising from the fuel. It is, perhaps, less essential now than was formerly the case that the lime used by the builder should be kept apart from the ash of the fuel, as in nearly all important works it is customary to prepare the mortar in a mill, which would crush up these substances along with the lump lime and incorporate them in the mortar.

[1] G. R. Burnell: *Limes, Cements, Mortars, etc.*

For use of the plasterer, the lime is slaked and run through a sieve, by means of which all the impurities and underburnt particles are eliminated. A much better-looking lime no doubt results from the use of kilns in which all contact with the fuel is avoided; and although the cost of doing this adds to the expense of burning, it is certainly worth while to endeavour, if possible, to keep out the ash and clinker.' [1]

Results of Calcination. 'Those limes which are obtained from the stones containing much silica in the composition of the clay, swell in setting, and are likely to dislocate the masonry executed with them. Those, on the contrary, in which the alumina is in excess, are likely to shrink and crack. The magnesian limestones, or dolomites, appear to be the least exposed to these inconveniences, and to retain without alteration their original bulk. The limes obtained from the Oxford Clay generally *swell*; those from the Chalk Marl *contract*.

'Limestones which contain many *fossils* produce a lime exposed to the risk of slaking at various and uncertain periods. Whether it arises from the fact that the decomposition of the animal matter had previously affected the nature of the limestone in contact with it, or from that of the different action of the calcination upon the shells, we mostly find that the fossiliferous limestones contain black spots which do not slake at the same time as the rest of the lime, or which retain their avidity for water to a later period; and in either case they swell and disintegrate the mass around them.' [2]

Testing Limes and Limestones

Berthier's Mode of Analysis. 'To ascertain whether a stone be, or be not, fit to be burnt for the purpose of obtaining a hydraulic lime, the following mode of analysis is sufficient for all practical purposes:—

'The stone should be powdered, and passed through a silk sieve; 10 grammes of this dust are to be put into a capsule, and by degrees muriatic acid is to be poured upon it, stirring it up continually with a glass or wooden rod; when the effervescence ceases, no more acid is to be added. The solution is then to be evaporated by a gentle heat until it is reduced to the state of a paste; it is then to be mixed with half a litre of water, and filtered; the clay will

[1] Redgrave and Spackman: *Calcareous Cements*, 2nd ed., p. 16.

[2] G. R. Burnell: *Limes, Cements, Mortars, etc.*

remain upon the filter. This substance is to be dried and weighed, the desiccation being made as perfect as possible. Lime water is then to be added to the remaining solution as long as any precipitation takes place from it. This precipitate must be collected as quickly as possible upon a filter ; it is then desiccated and weighed. It is magnesia, often combined with iron and manganese.' [1]

'**The condition of the silica** present in impure limestones has an important influence on their value when employed for the manufacture of hydraulic lime. Any silica existing in the uncombined state as quartz-sand is unacted upon by the lime at the comparatively low temperature of the kiln, and consequently after calcination it does not separate as a gelatinous bulky mass, as is usual with the silica in samples of hydraulic lime, when treated with hydrochloric acid. Further, it is unacted upon by a boiling solution of sodium carbonate, and it is not in a condition to enter into combination ; it is present, in fact, simply as inert matter. In order to confer hydraulic properties upon the lime much of the silica must, before burning, occur in combination, preferably with alumina.

'Many of the beds of impure limestone in the Carboniferous deposits contain free silica as sand in considerable quantity. Lime prepared from stone of this description is easily recognised by its friable granular appearance, while, on the other hand, that which is burnt from stone in which the silica exists in combination with other substances, as is the case in the beds of the Lias formation and in some of the Carboniferous deposits, has a dense, close, even structure, the lumps of quicklime ringing when struck together.' [2]

'When **treated with muriatic acid**, a limestone that leaves about 10 per cent. of insoluble matter forms, according to M. Lipowitz (*Manufacture of Cements*), a tolerably hydraulic lime ; but when leaving from 20 to 30 per cent., such a lime will not slake after burning without first being powdered, after which process it often produces the best hydraulic mortar. After calcination and slaking, such limestones as the Blue Lias require careful screening to remove unburnt cores, not more than 1½ sand to 1 of lime, and are often improved in hydraulicity by the addition of a small percentage of pounded surface-clinkers.' [3]

[1] G. R. Burnell: *Limes, Cements, Mortars, etc.*
[2] Redgrave and Spackman: *Calcareous Cements*, 2nd ed., p. 11.
[3] David Page: *Economic Geology*, p. 95.

Cements

'**The energy** of a cement depends upon the rapidity with which the lime and the silica, or the lime and the alumina, combine in the presence of water to form stable compounds, or with which the ready-formed silicates and aluminates become hydrated when water is added. We have thus the quick-setting cements of the Roman cement type, which become indurated mainly by hydration in a few minutes, and the dense cements resembling Portland, which depend for their induration on a rearrangement of the silicates, and which may take as many hours to set as the former substance does minutes.

'It should be here noted that when we speak of the setting of cements we imply the act of induration and not the mere absorption of the water, which is most characteristic of the imperfect setting action of a lime mortar.' [1]

Influence of Calcination. 'The calcination of these varieties of cements plays a very important part in their subsequent behaviour, when tempered with water. Thus it is possible from the same clay-limestones to prepare (*a*) a hydraulic lime; (*b*) a quick-setting cement; and (*c*) a cement resembling Portland cement in character.

'At a low temperature in the kiln the mixtures of lime and clay have not mutually reacted the one on the other, and we obtain a material in which the energy due to the hydration of the lime overcomes the tendency of the silicic acid to enter into combination with this lime, under the agency of water.

'When the second stage in the calcination is reached the silicic acid is liberated or rendered capable of attacking the lime, yielding a cement which sets with comparative rapidity. While, lastly, under still more intense firing, the stage of calcination is approached when silicates and aluminates are formed in the kiln and when the material acts like a Portland cement, and when the iron, moreover, which had during the first and second degrees of calcination remained in the condition of a peroxide, passes into that of a protoxide (as is always the case in perfectly prepared Portland cement). This change in the oxide of iron is only effected at very high temperatures, and furnishes a certain indication of the production of a dense, slow-setting cement.

'If, in the case of this clayey limestone, the clay had been less

[1] Redgrave and Spackman: *Calcareous Cements*, 2nd ed., p. 10.

in quantity, we should have obtained a hydraulic lime which would slake with difficulty, and which would be liable to the evil effects of "after-slaking." If the proportion of the bases contained in the clay, relatively to the amount of silicic acid present, had been greater, the mass would have probably become vitrified or partially fused before the temperature necessary for the final stage of calcination was reached.' [1]

Natural Cements

Natural cements are burnt direct from stones containing from 20 to 40 per cent. of clay, the remainder consisting chiefly of carbonate of lime alone, or of carbonate of lime mixed with carbonate of magnesia.

Natural rocks of suitable composition for Portland cement are found in France and in America, but as they contain insufficient lime as a rule, they are chiefly used for the manufacture of Portland cement, a small percentage of purer limestone being added.

Roman Cement. 'A peculiar class of the argillaceous limestones yields on calcination a species of lime capable of setting under water with considerable rapidity, of acquiring a great degree of hardness within a very short space of time, and of being employed without the admixture of any foreign substance. The first discoverer of this kind of cement was Mr Parker, of London, who in the year 1796 took out a patent for the manufacture of what he called Roman cement, from the septaria nodules of the London Clay formation, found in the Island of Sheppey. His process consisted in calcining the stone, previously broken into small fragments, to a point equal to the commencement of vitrification, and then reducing it to powder by some mechanical operation.

'Subsequently a similar material was found at Harwich and in Yorkshire, also on the coast of France and in Burgundy, and doubtless it is to be met with in all the marl beds intercalated between the principal stages of the Limestone formations, and very frequently in the Tertiary clays, in the form of detached nodules of a dark-coloured, argillaceous limestone traversed by veins filled with calcareous spar. The colour is sometimes blue, especially when the nodules are obtained from the Lias; sometimes brown, or a deep red, in the Tertiary formations, owing to the presence of the oxide of iron in very considerable quantities.

[1] Redgrave and Spackman: *Calcareous Cements*, 2nd ed., pp. 10–11.

'The mineralogical composition of the stones from which the cement is made differs very much; but the characteristic type may be said to consist of above 30 and below 60 per cent. of clay and other extraneous matter in combination with the carbonate of lime. The Sheppey stone usually contains 55 parts of lime, 38 of clay, and 7 of iron; the Yorkshire stone contains 34 parts of clay, 62 of carbonate of lime, and 4 per cent. of iron; the Harwich stone contains 47 parts of clay, 49 of carbonate of lime, and 3 of oxide of iron.

'The cement stones are burnt in conical kilns with running fires, and, in England at least, with coke or coal. The mode of burning requires a considerable degree of attention, for experience has demonstrated that Parker was mistaken in supposing that a commencement of vitrification was necessary. On the contrary, the practice of manufacturers at the present day is rather to underburn the cement, with the object of economising the expense of grinding. This material differs in this respect also from the ordinary limes, that the precise point of calcination does not appear to affect its qualities.

'Before being burnt, the stone is of a fine close grain, of a peculiar pasty appearance; the surfaces of fracture are rather greasy to the touch, and somewhat warmer than the surface of the stone Examined with the microscope, it exhibits many sparkling points, which may be either crystals of carbonate of lime or of some of the other constituents. It sticks easily to the tongue; it does not strike fire; its dust, when scraped with the point of a knife, is a greyish white for the most part, especially when derived from the Blue Lias formation. It effervesces with nitrous acid, and gives off nitrous acid gas. During calcination the cement stone loses about one-third of its weight, and the colour becomes of a brown tinge, differing with the stones from which the cement is obtained. When burnt it becomes soft to the touch, and leaves upon the fingers a very fine dust; and it sticks very decidedly to the tongue.'[1]

Roman cement has nothing like the strength of Portland, and must be used quite fresh as, if exposed to the air, it becomes inert.

Magnesium Cements of America. 'These are either rock cements composed of bisilicates of lime and cement, or trisilicates of lime, magnesia, and alumina. The bisilicates are, as a rule, of the

[1] G. R. Burnell: *Limes, Cements, Mortars, etc.*

Portland cement type, and are frequently calcined at a white heat; the trisilicates are fired at a lower temperature, and are more of the nature of Roman cement.[1]

Selenitic Cement. The addition of 5 to 10 per cent. of plaster of Paris to lime increases the hardening properties of the latter by 50 to 100 per cent., and this mixture is sometimes known as selenitic cement.

Portland Cement

This material is obtained by burning to a clinkering temperature an artificial mixture of calcareous and argillaceous and/or other silica, alumina, or iron oxide-bearing materials, and grinding the resulting clinker so as to be capable of complying with the British standard or other suitable specification.

The **raw materials** consist of calcareous materials such as chalk, limestone, marine shells, etc., and alumina and silica-bearing materials such as clay, shale, slate, etc., and some form of slag; or they may be natural mixtures of calcareous and argillaceous constituents such as marls, gault clays, cement rock, etc.

The raw materials are then ground and either damped and taken direct to the kilns (dry process), or mixed with water to form a slurry and then pumped into the kilns (wet process).

After heating to near vitrification the clinkers are ground after cooling.

Composition. The chemical composition varies over rather a wide range. The specification gives the following limits:—

Magnesia not above 4 per cent.

Insoluble residue not above 1 per cent.

Loss on ignition not above 3 per cent. for cement tested in temperate climates, or 4 per cent. for cement tested in hot climates.

Total sulphur calculated as sulphuric anhydride not above 2·75 per cent.

The ratio of lime to silica and alumina calculated to chemical equivalents to be between 2·0 and 3·0. The lime is approximately 55 to 70 per cent., alumina 4 to 12 per cent., and ferric oxide 2 to 4 per cent.

Materials available for Portland Cement. 'It is now perfectly well known that suitable mixtures of carbonate of lime and clay can be prepared from raw materials, to be found in all parts of the world, and in many geological formations. It is not essential

[1] Redgrave and Spackman: *Calcareous Cements*, 2nd ed., p. 25.

that the mixture should be made of each of these substances in the pure state. They occur naturally compounded in various proportions in vast beds in many different localities, and in making use of such materials, all that is necessary is to employ them in such proportions as will give the required quantity of carbonate of lime in the mixture.

'As examples of pure or nearly pure materials, we may instance the white chalk of the Thames district, the indurated chalk of the north of Ireland, and many deposits of the Carboniferous limestone formation, all of which contain about 98 per cent. of carbonate of lime. Among the clays and shales in use for cement-making (under the latter term we imply a solid form of clay compacted by pressure and capable of being split into laminæ), we have the alluvial mud of the Medway—a salt-water deposit—the freshwater alluvium found on the banks of many rivers, boulder-clay, the shales and clays of the Coal Measures, and the shales of the Silurian formation, in which last lime is either entirely absent or present in very small quantities. As instances of naturally compounded materials, we may mention the Lower or Grey Chalk of the Medway, the limestones and shales of the Lias and of the Upper Carboniferous strata, Gault clay, the Chalk Marls of Cambridgeshire and Germany, and the Silurian limestones now so widely used in the Lehigh Valley district of Pennsylvania.' [1]

Characteristics of Clays adapted for Cement-making. 'The best clays for the use of the cement-maker are those which are highly siliceous, even if much of the silica occurs in the free state as fine sand. Should the silica be present as a coarse-grained sand, the mixture requires to be very perfect and firmly ground. Experience shows that in the finished cement the silica, even from a sandy clay, is found in the soluble form. This is not the case in burning such clayey substances into a hydraulic lime, as the temperature reached is not sufficiently high to effect this change. The proportion of silica present should at least equal 2½ times the amount of the iron oxide and alumina taken together. Thus a clay containing 18 per cent. of alumina and 6 per cent. of ferric oxide should contain at least 60 per cent. of silica. Clays of this composition require a high temperature to effect their fusion when they are employed in conjunction with carbonate of lime. The resulting cement sets in a reasonable time, speedily attains sufficient strength to show good breaking tests, and steadily increases in strength with

[1] Redgrave and Spackman: *Calcareous Cements*, 2nd ed., p. 45.

age. On the other hand, clays with a high percentage of alumina yield a much more fusible mixture, which can be calcined with less fuel, but which often causes trouble in the kiln by over-burning. The finished cement sets quickly, often indeed with such rapidity as to render its use difficult without regauging, and the strength at short dates runs high. There is little increase with age, indeed often a tendency to retrograde action.' [1]

Proportions of the Ingredients. The engineer will do well to insist on cement being up to B.S.S., as comparatively small differences in proportions of the principal ingredients may wreck his work. *E.g.* a cement which is *over-clayed* sets quickly and never becomes thoroughly indurated, and has a tendency to crumble when exposed to the weather. A cement which is *over-limed* is liable to 'blow' or swell in the work.

The amount of *sulphur* present is also important, for calcium sulphate is comparatively soluble in water, and calcium sulphide is a most dangerous ingredient.

For further information as to nature of ingredients and processes of manufacture, storage, etc., the engineer is referred to the *Encyclopædia Britannica* and text-books, *e.g.* Redgrave and Spackman's *Calcareous Cements.*

RAPID HARDENING CEMENTS

Ferrocrete was the first rapid hardening Portland cement to come on the market, and has been followed by others. All are true Portland cement, but made with such refinements in manufacture, especially in fine grinding of the raw material and the finished product, as to produce superlative quality.

Aluminous cement was originally made in France, but is now made in England, the 'Lightning' brand being one of the best known. It consists essentially of a mixture of impure bauxite (which is largely composed of alumina) and lime. It has the same constituents as Portland cement but in different proportions—viz. about 6 per cent. silica, 35 per cent. alumina, 5 per cent. iron oxide, and 35 per cent. lime, as compared with proportions of constituents of Portland cement given above.

The aluminous clinker is fused or melted, and not merely brought to a state of incipient fusion as in Portland cement. The fused material is much harder than Portland cement clinker and takes longer to grind.

[1] Redgrave and Spackman: *Calcareous Cements*, 2nd ed., p. 46.

Aluminous cement has the advantage of comparative immunity from attack by frost while setting. When apparatus that has been used for Portland cement is used for aluminous cement, every article must first be carefully cleaned, as contamination with Portland cement is liable to cause 'flash' setting.

Calcium Sulphate Cements

This class includes cements which primarily depend upon the hydration of calcium sulphate for their hardening and setting properties, and includes plaster of Paris, Keene's cement, Parian cement, etc. The raw material is gypsum.

All these cements are suitable only for indoor work, as they are soluble in water.

Plaster of Paris, so largely employed in France both for external and internal work, but with us chiefly for interior mouldings and ornamentation, is derived from common gypsum or sulphate of lime. Gypsum occurs in several formations, but in Europe it is found mainly in the Trias and Tertiary, its presence in beds of great purity in the Wealden being a recent discovery of the sub-Wealden borings. In Britain, available supplies can be obtained from Chellaston in Derbyshire, Syston in Leicestershire, Tutbury in Staffordshire, Droitwich in Worcestershire, Cardiff in Glamorganshire, and at Kirkby-Thore in Westmorland, the beds being of various colours, texture, and purity. Being baked in ovens to discharge its water of crystallisation, it falls into a soft white powder (the plaster of Paris of commerce); and this powder, when worked into a paste with water, though plastic and pliable for a while, soon sets hard with considerable strength and solidity. When mixed with glue instead of water, plaster of Paris becomes *stucco.*

Keene's and Parian Cements. If, instead of being used with water, plaster of Paris, in fine powder, is thrown into a vessel containing a saturated solution of alum, borax, or sulphate of potash, and after soaking for some time is taken out, rebaked, once more reduced to powder, and then moistened with a solution of alum, a hard plaster is obtained that takes a high polish. This plaster is called *Keene's cement* if made with alum; *Parian* with borax; and *Martin's* with pearl ash.

These plasters are generally used for forming arrises, where ordinary plaster is used for walls which are required to be painted, such as bathrooms, etc.

GEOLOGICAL DISTRIBUTION

General Laws. 'A knowledge of the laws which appear to regulate the geological distribution of the rocks which supply hydraulic and other limes may prevent many useless researches and save perhaps some injudicious outlay of capital.

'It is known, to quote nearly the words of M. Parandier, that every stratified geological formation comprehends a series of beds, whose deposition corresponds with the various periods of existence of the marine basin in which they were formed, which marine basin must have had its hydrographical limits, its affluents, etc. In the first periods, immediately after the cataclysms and the great erosions (which, in disturbing the *status quo* of the preceding geological epoch, had given rise to the new order of things), the sedimentary deposits must principally have owed their origin to the matters held in suspension in the liquid. They must have taken the form, for the most part, and throughout the whole extent of the basin, of agglomerated rocks, sandstones, clays, etc., except in the isolated points of the affluents, in the great depressions of the bottom, and in the very deep waters, where the materials brought down by the currents could not arrive, and where the beds took a degree of compactness different from that which is to be found on the borders of the basin. By degrees the matters held in chemical suspension in the waters, and which were in the beginning mingled with those in mechanical suspension thus brought down, began to deposit, in greater relative proportions, as soon as the geological condition of the basin had resumed a normal state. At times recurrences of the great agitations of the strata were reproduced in the same geological epoch, but always during a shorter period, and, with less intensity, with the same phenomena.

'Thus, in the lower divisions of the secondary strata, we find the marls, the siliceous sands and clays, the calcareous marls, the ferruginous strata; then the limestones with all the different varieties of texture and composition; and lastly, we find the magnesian limestones. The contact of certain formations either contemporaneous with, or posterior to, the formation of the different strata often modifies these last. The presence of certain ingredients, and the secular action of the exterior agents, also often produce very remarkable modifications or alterations, and even some molecular transformations, which are very curious, changing the

chemical and physical properties of the rocks. But these phenomena have their particular laws, and their definite epochs of appearance, and we can calculate with a tolerable degree of certainty upon the extent of their action.'[1]

Probable Position of Different Materials. 'It is easily to be conceived, from what is stated above, that we should be able to predicate within certain limits the points at which the rocks are likely to contain the elements the most favourable to the attainment of the object in view in such researches as the one before us. The materials likely to furnish us the sands and clays fit to be converted into *artificial pozzuolanas* are generally to be met with at the bottom of the sedimentary formations. The *limestones* likely to yield hydraulic limes occur amongst the marly or argillaceous beds, or at the points where these last pass into the purer calcareous rocks, and which are marked by the intercalation of strata of limestones and clays. The upper members of all the series may be regarded as being too free from argillaceous matter to furnish anything but rich limes.

'Amongst the secondary formations we find, for instance, that the Lower Chalk marl passes into the clays of the Gault, or the Upper Greensand, and that it yields a lime which is often eminently hydraulic. In the Greensand there are few solid calcareous rocks; there are few also in the lower members of the Cretaceous formations below the Greensand. Hydraulic limes are to be obtained from the beds of limestone intercalated between the marls of the Kimmeridge Clay; in the Oxford Clay, at the passage between the upper and lower calcareous groups of this division of the sedimentary rocks; and in the Liassic series.'[1]

Lias Lime. 'In England, where the "rule of thumb" prevails so extensively, it is the general practice to receive the Blue Lias lime as a good and a satisfactory hydraulic lime in all cases, and without any regard to the positions in the series that the beds of that formation may occupy. It is, however, necessary to remark that every bed of the Blue Lias limestone contains a different proportion of the silicate of alumina, in combination with the carbonate of lime, and that therefore the powers of setting under water must be very different in the limes obtained from them. Even at the base of the Liassic series, the differences that occur are as great as between about 8 per cent. of the silicate of alumina and 90 per cent. of carbonate of lime, and 64 per cent. of the former ingredient to

[1] G. R. Burnell: *Limes, Cements, Mortars, etc.*

34 per cent. of the latter. The first of these would yield only a moderately hydraulic lime; the latter would yield, on the contrary, a most energetic cement, if burnt and ground. The peculiar properties of the Blue Lias lime have been established upon the results that have followed the conversion of the middle beds of the series, which contain from 16 to 20 per cent. of the silicate of alumina. It would be, of course, easy to distinguish the best qualities of Blue Lias lime, as in fact it is easy to predicate the nature of any description of that material. Thus the lumps of burnt limestone should be rather large, and they should present on all sides a conchoidal fracture; the lime should swell but little in slaking, and it should not give out much heat, nor yield to the effect of the water before about two to five minutes. A lime of this description requires to be slaked before being mixed with the sand for use in a building; but as some builders have a fancy for the employment of lime "hot," as they call it, it is safer to employ the Blue Lias lime after being ground. The best descriptions of Blue Lias lime are obtained from Warwickshire, Leicestershire, Dorsetshire, the neighbourhood of Bath, Aberdare, Rugby, etc.; but they are all of them of very variable composition, and they require to be used with great precaution; at least until the precise nature of the beds has been ascertained, or until a test for the hydraulicity has been carried out.' [1]

British Limestones. 'The limestones, which lie at the foundation of all limes, mortars, and cements, are abundantly diffused through the stratified formations, there being scarcely a system which does not present one or more horizons of calcareous deposits. Indeed, every system, from the oldest to the most recent, has its limestones: the Metamorphic, its crystalline marbles; the Silurian, its coralline and shelly beds; the Old Red, its cornstones; the Devonian, its coralline and shelly marbles; the Carboniferous, its coralline, encrinal, shelly, and freshwater beds; the Permian, its dolomites; the Trias, its muschelkalks; the Jurassic, its oolites; the Wealden, its shelly beds; the Cretaceous, its chalks; the Tertiary, its gypseous and nummulitic strata; and the Post-Tertiary, its lacustrine marls.

'In Britain the most of these are abundantly developed; and for its area few countries can boast of such a varied and available supply. As mixed rocks they vary, of course, in composition, some being almost pure carbonates, some dolomitic or magnesian,

[1] G. R. Burnell: *Limes, Cements, Mortars, etc.*

and others sulphates or gypsums; while these varieties may again be more or less siliceous, argillaceous, ferruginous, or bituminous.

'Whatever the varieties, or in whatever formations they may occur, the most of these limestones come to the surface in long stretches of outcrop, and are consequently quarried in open workings; hence the numerous openings, great and small, on the chalks, oolites, magnesian limestones, and mountain limestones of England, and the mountain limestones of Ireland. England and Ireland are magnificently supplied with limestones; Scotland but scantily so, and hence the more frequent recourse to mining of it in that country, as well as to its importation from the north of England and Antrim.' [1]

'The Lias of England, which stretches across the country from Whitby on the north-east to Lyme Regis in the south-west, is our main repository of water-setting limestones (Blue Lias); but available beds also occur among the Carboniferous limestones of Flintshire (Heublas), Northumberland, Lanarkshire (Arden, Hurlett), coast of Fife (Blebo, etc.), and in the Lothians at Dunbar, Cousland, and other places. Such beds may be distinguished in the field by their tougher and earthier texture—never being so crystalline as mortar limestones—by their not effervescing so violently under acids, and by their weathering more slowly into a deeper brown surface.

'Some of the argillo-calcareous ironstones known as "curl" or "cone in cone," containing about 10 per cent. of iron, are also used (Coalbrook Dale) in the manufacture of hydraulic cements; and the septaria from the Lower Lias and London Clay are well known to cement-makers for their strong and energetic hydraulicity.' [2]

Indian Limestones. *Kankar* is a species of subsoil tufa, formed by the deposition of calcareous matter extracted by the surface-waters in minute portions from the beds of sand and clay, and redeposited in a concentrated and irregular form. Its qualities vary very much, but it is frequently hydraulic owing to being deposited in a clay bed, and as such is used for lime. Harder varieties are used for road metal.

[1] David Page: *Economic Geology*, p. 90.

[2] David Page: *Ibid.*, p. 94.

CHAPTER XI

ROADS AND CANALS

SECTION I. ROAD CONSTRUCTION

Road engineering is a special branch of engineering on which many treatises have been written and, no doubt, more will be forthcoming, as the results of many more or less experimental methods adopted for modern roads become known.

In this chapter it is only possible to refer briefly to the main principles of road construction, in connection with which a knowledge of geology is, perhaps, more important than in any other branch of engineering.

On many roads in this country there appears to be a tendency to ignore the essential principles of road construction, and to depend very largely on a thin crust of reinforced concrete.

The neglect of 'banking' or super-elevation, without which no road can be safe for fast (or even moderate) traffic in hilly districts, and which is just as necessary for fast traffic in ordinary undulating country; the arguments in favour of concrete laid continuously, which can be disposed of by reference to Canadian practice; and the very common neglect of really adequate drainage, are matters to which our road engineers might give more attention.

The **main essentials** for a satisfactory highway are (i) a perfectly drained *sub-grade* or formation surface, and (ii) a *road-covering* consisting of (*a*) a solid foundation or *bottoming*, and (*b*) a *surface coating* which may include one or more coats of metal, concrete, or other material, with a final coat or 'carpet' of asphalt, bitumen, or gravel, etc.

The term 'foundation' is often applied to the subsoil or rock on which the sub-grade is prepared, as well as to the bottoming of the road covering. So the term *sub-grade foundation* will be used hereafter for the former, and the term *bottoming* for the actual foundation of the road covering.

The term *sub-crust* is sometimes used for the foundation or bottoming, but the same term is also used for the lower of the two coats of metal, and will therefore be avoided in this book.

The Alignment

Value of Geological Knowledge. In choosing the alignment for a new road, it is important to study the geological nature of the country to be passed through, especially with regard to the following points :—

(*a*) The nature of the subsoil or rock on which the formation level is to be made or where cuttings or embankments are proposed.

(*b*) The all-important question of drainage, so as to avoid subsoils difficult to drain, *e.g.* clays.

(*c*) Whether to avoid expensive cuttings, or to decide that they are worth while, in view of the rock or other material to be excavated being such as can be profitably used elsewhere.

(*d*) How to avoid marshy or boggy sites for embankments.

The **main considerations** which decide the alignment are (1) ruling gradient; (2) shortness, consistent with flat gradients, least rise and fall, and economy of construction; (3) curves of minimum radius; (4) economy of earthwork, culverts, and bridges; (5) the requirements of the district. But in some instances it may be worth while to deviate from the selected track in order to come in closer proximity to quarries, clay-pits, and coal-fields—the increasing traffic arriving therefrom may become a source of income for the permanent maintenance of the highway.

The first step is to ascertain the position of the watercourse and watershed lines of the district to be passed through. The general direction having been selected, the river-crossings must be decided upon, and the points determined at which the watersheds are to be crossed. The approaches to the bridges must be carefully set out, and the ascents to and descents from the watershed, contoured, where they are to be in side-cutting, from the summits downwards, so as to ascertain the points at which the hills are to be entered.

Before the route is finally decided upon, two or more trial lines should be run between the points thus fixed, and the country carefully examined on each side of these lines, to see which best complies with the main considerations detailed above. The actual survey can then be proceeded with.

Reconnaissance. 'The general series of operations preliminary to the formation of a new line of communication are the examination or reconnaissance of the country between the points to be connected, taking note of the physical features of the country, its geological

formation and sources from which materials for construction may be obtained, and the probable requirements of the district to be passed through. In this work the engineer will be greatly aided by obtaining the best and most reliable maps of the district. Flying-levels are generally taken concurrently, in order to ascertain the elevations of detached points, such as passes across ridges, and valleys, also points where structures of magnitude may be required.

General Principles in the Field. 'In laying out a line for a new road, the following data should be carefully noted and recorded in the field-book :—

'Examine the inclination of the strata, their nature and condition as to dryness.

'Have the surface of road exposed as much as possible to the action of the air and sun's rays.

'Cross valleys and passes at right angles.

'Examine beds of rivers at proposed crossings, and up and down stream, with a view to secure stable foundations for bridges, culverts, etc.

'Examine sources, accessibility, and distances of the supply of material for the erection of structural works, and for stones suitable for the road-covering.

'Ascertain accurately the level of all existing lines of communication, such as railways, roads, canals, and of rivers and streams.' [1]

Road-cuttings. 'Having selected a route, the engineer has next to inquire what excavations, what embankment, and what bridges will be necessary to render the road of easy traction as to gradients. In the matter of excavation it requires some skill, according as the cutting may be through tough boulder-clay—through an admixture of drift sands and clays, which are apt to slip by the percolation of water—through greenstones and basalts, which, though expensive to remove, may be utilised as road-material—or through sandstones and limestones which may be applied to the erection of bridges and retaining walls. Some acquaintance with the structure of rocks will also be of use to the engineer, in so far as these may be jointed or full of "backs and cutters" like some limestones; columnar or sub-columnar, like basalts and greenstones; tabular, as granites; or in alternate hard and soft strata, as sandstones and shales. Every formation has its own lie and structure, and excavating in accordance with these is always the cheapest and most expeditious

[1] Thomas Aitken: *Road-making and Maintenance*, 2nd ed., pp. 44–45.

method. Where the material is of uniform character, little care is needed either as regards retaining walls or slope of excavation; but where the material is of unequal durability, as alternations of sands and clays, of sandstones, shales, and clays, the weathering of the softer beds is sure to ensue, and should be protected by facing up immediately after excavation. From want of this precaution—and especially in railway cuttings—much of the expense has often been entailed, and that not till obstructions and accidents have happened through slips and falls—such contingencies of themselves costing ten times the amount of any walling-up that might have been at first adopted. Some care is also necessary when excavations pass through strata at high angles, so as to prevent slips from the rising side; and when water-bearing beds occur, free egress must be made for the outflow, which otherwise would, in process of time, bring down the strongest retaining wall. Where cuttings pass through rocks suitable for building or for roads, a free face should be kept, if possible, for future quarrying—the situation being so available, not only for the working, but for the removal of the quarried material.' [1]

Side-slopes. 'The forming of the side-slopes requires considerable attention, so as to ensure stability and prevent slipping. The resistance to slip arises partly from the friction between the grains composing the soil and partly from their mutual adhesion. Friction is, however, the only force which can be relied upon for permanent stability, as the adhesion of the earth is destroyed by the action of air and moisture, this being especially the case during alternate frost and thaw. The nature of the soil, its condition as to internal moisture and the atmospheric influence, therefore, combine in fixing the inclination of the side-slopes. The *angle of repose*, or, as it is generally termed, the natural slope at which different kinds of earth, by friction alone, will remain permanently stable, is shown in the table given by Professor Rankine in his *Civil Engineering*, *vide* Table IV.

'The slopes most frequently adopted for earthwork are 3 to 2 and 2 to 1, corresponding to the angles of repose $33\frac{1}{2}°$ and $26\frac{1}{2}°$ nearly.' [2]

'With regard to the slope necessary to be given to the side of an embankment or cutting, this should always be less than the inclination which the earth naturally assumes, and which varies according

[1] David Page: *Economic Geology*, p. 107.

[2] Thomas Aitken: *Road-making and Maintenance*, 2nd ed., p. 58.

TABLE IV

Earth	Angle of repose	Coefficient of friction	Customary designation of natural slope
Dry sand, clay, and mixed earth	from 37° to 21°	0·75 0·38	1·33 to 1 2·63 „ 1
Damp clay	45°	1·00	1 „ 1
Wet clay	from 17° to 14°	0·31 0·25	3·23 „ 1 4 „ 1
Shingle and gravel	from 48° to 35°	1·11 0·70	0·9 „ 1 1·43 „ 1
Peat	from 45° to 14°	1·00 0·25	1 „ 1 4 „ 1

to the nature of the soil, as will be observed from the following details given by Sir H. Parnell: " In the London and plastic *Clay* formation it will not be safe to make the slopes of embankments or cuttings that exceed 4 feet high with a steeper slope than 3 feet horizontal for 1 foot perpendicular. In cuttings in chalk or chalk marl the slopes will stand at 1 to 1. In *sandstone*, if it be hard, solid, and uniform, the slopes will stand at a ½ to 1, or nearly perpendicular.

' " If a sandstone stratum alternate with one of clay or marl, it is difficult to say at what inclination the slopes will stand; this will, in fact, depend upon the inclination of the strata. If the line of the road is parallel to the line of the bearing of the strata, in such cases large masses of the stone become detached, and slip down over the smooth and glassy surface of the subjacent bed. There are many instances of slips in sandstone and marl strata under such circumstances as those now described, and here the slopes are as much as 4 to 1. If the road is across such strata, or at right angles to the line of bearing, then the slopes may be made 1½ to 1; but if the strata lie horizontal, even though there should be thin layers of marl between the beds of stone, the slopes will stand at a ½ to 1. But it will be necessary, if the beds of marl exceed 12 inches in thickness, to face them with stone."

' If any beds of gravel or sand are found intermixed with clay, drains should be cut along the top and even in the sides of the cuttings; for if this precaution be not taken, the water, which will find its way into the gravel, will, by its hydrostatic pressure, force the body of clay down before it, and slips will take place even when the inclinations are as much as 4 to 1; and when this occurs it is extremely difficult to re-establish them.

'In limestone strata, if they be solid, slopes will stand at a ¼ to 1; but in most cases limestone is found mixed with clay beds, and in such cases the slopes should be 1½ or 2 to 1. In the primitive strata such as granite, slate, or gneiss, slopes will stand at a ¼ to 1.'[1]

'In excavations through *solid rock*, which does not disintegrate on exposure to the atmosphere, the sides might be made perpendicular; but as this would exclude, in a great degree, the action of the sun and air, which is essential to keeping the road-surface dry and in good order, it is necessary to make the side-slopes with an inclination varying from 1 in 1 to 2 in 1, or even more, according to the locality, the inclination of the slope on the south side in northern latitudes being made less steep in order that the road-surface may be more exposed to the sun's rays.

'The *slaty rocks* generally decompose rapidly on the surface, when exposed to moisture and the action of frost. The side-slopes in rocks of this character may be cut into steps, and then be covered by a layer of vegetable mould sown with grass seed, or else the earth may be sodded in the usual way.

'The *stratified* soils and rocks, in which the strata have a dip or inclination to the horizon, are liable to *slips*, or to give way, by one stratum becoming detached and sliding on another; which is caused either from the action of frost or from the pressure of water, which insinuates itself between the strata. The worst soils of this character are those formed of alternate strata of clay and sand, particularly if the clay is of a nature to become semi-fluid when mixed with water. The best preventives that can be resorted to in these cases are to adopt a system of thorough drainage, to prevent the surface-water of the ground from running down the side-slopes, and to cut off all springs which run towards the roadway from the side-slopes.'[2]

Drainage of Side-slopes. 'The slopes in cuttings on sidelong ground are generally the most troublesome, and great pains should be taken in order to thoroughly intercept, from the rising ground, any flow or filtering of water towards the road bed. This is readily accomplished by forming catch-water ditches or drains on the uphill side of the cutting a few feet back from the crest of the slope or point where the excavation joins the natural surface of the ground. These, if possible, should be carried to the most convenient watercourses; but where the surface of the ground is such that a sufficient fall cannot be obtained unless at great expense in cutting and laying

[1] Frank Latham: *The Construction of Roads, Paths, and Sea Defences*, pp. 25–26.
[2] H. Law: *Rudiments of the Art of Constructing Roads*, pp. 44–45.

drain pipes, the water may be conveyed down the slope to the side channel or covered drain near the formation level.' [1]

'Where slips occur from the action of *springs*, it frequently becomes a very difficult task to secure the side-slopes. If the sources can be easily reached by excavating into the side-slopes, drains formed of *layers of fascines*, or brushwood, may be placed to give an outlet to the water, and prevent its action upon the side-slopes. The fascines may be covered on top with good sods laid with the grass side beneath, and the excavation made for the drain filled with good earth well rammed. Drains formed of *broken stone*, covered in like manner on top with a layer of sod to prevent the drain from becoming choked with earth, may be used under the same circumstances as fascine drains. Where the sources are not isolated and the whole mass of the soil forming the side-slopes appears saturated, the drainage may be affected by excavating trenches a few feet wide at intervals to the depth of some feet into the side-slopes, and filling them with broken stone, or else a general drain of broken stone may be made throughout the whole extent of the side-slope by excavating into it. When this is deemed necessary, it will be well to arrange the drain like an inclined retaining wall, with buttresses at intervals projecting into the earth further than the general mass of the drain. The front face of the drain should, in this case, also be covered with a layer of sods with the grass side beneath, and upon this a layer of good earth should be compactly laid to form the face of the side-slopes. The drain need only be carried high enough above the foot of the side-slope to tap all the sources; and it should be sunk sufficiently below the roadway surface to give it secure footing.

'The drainage has been effected, in some cases, by sinking *wells* or *shafts* at some distance behind the side-slopes, from the top surface to the level of the bottom of the excavation, and leading the water which collects in them, by pipes, into drains at the foot of the side-slopes. In others, a narrow trench has been excavated, parallel to the axis of the road, from the top surface to a sufficient depth to tap all the sources which flow towards the side-slope, and a drain formed either by filling the trench wholly with broken stone, or else by arranging an open conduit at the bottom to receive the water collected, over which a layer of brushwood is laid, the remainder of the trench being filled with broken stone.' [2]

[1] Thomas Aitken: *Road-making and Maintenance*, 2nd ed., pp. 62–63.

[2] H. Law: *Rudiments of the Art of Constructing Roads*, pp. 45–46.

MOUNTAIN ROADS

Alignment. In selecting the most suitable line for a mountain road the following points should be taken into consideration :—

(1) The most direct route is not always the best.

(2) Ruling points such as crossings of rivers and streams, saddles, etc., should be fixed first. Marshy places should be avoided, as the cost of drainage is likely to be prohibitive.

(3) It is often better to go round a hill than to go over the top. Zigzags are often essential, in order not to exceed the maximum gradient. It is very important—and this point is often neglected—that the turning-points joining the straight portions of the road should be almost, if not quite, level.

Other important points which influence the selection of a route are :

(1) Stratification.

(2) Whether the route is sunny or sheltered.

(3) Nature of material which will be quarried from cuttings.

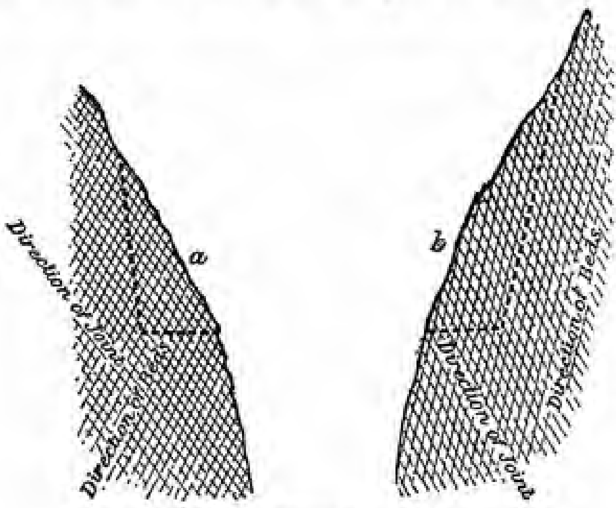

FIG. 41. Road-cuttings in mountain pass.

Stratification. Carefully examine the stratification of the rocks to be cut through, and avoid if possible all strata dipping towards the line of road. Thus in fig. 41 the side-cutting at *a* would not be safe, whilst that at *b* would be perfectly secure.

It sometimes happens that advantage can be taken of the natural stratification to economise work in a long side-cutting. This was done by Mr E. Dobson in the case of a road over Evan's Pass, at Port Lyttelton, New Zealand. The descent of the pass was on the side of a long volcanic spur, formed by a succession of lava streams, dipping at an angle of 1 in 12, the lower part of each lava stream being hard volcanic rock, whilst the upper portion was soft and easily worked. The line was originally set out with a gradient of 1 in 17, which would have entailed a series of cuttings through the hard rock and retaining walls in front of the softer portions. By altering the gradient, however, to that of the lava streams, a solid floor was obtained throughout, the retaining walls were dispensed with, and the excavation was made chiefly in soft material. The alteration effected considerable saving in time and first cost, as well as in the cost of maintenance.

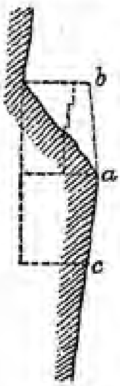

Fig. 42. Road-cutting in mountain pass.

'It is desirable to run a *trial gradient* through the work, and find where it intersects difficult ground. Then lay out the line at these points so as to obtain the most advantageous levels for the execution of the work, and readjust the gradient as may be required. For instance, in fig. 42, if the level of the road is fixed at *a*, the floor of the cutting will be in the solid with tight side-cutting; if at *c*, the available width would be considerably reduced, and the amount of cutting increased; whilst if the level were at *b*, a retaining wall would be necessary.'[1]

Crossing Watersheds. '(1) *When the route lies across the valleys*, as in the case of a road parallel to a coast-line passing over the spurs of a coast-range. Two modes of treatment are possible. Either the crests of the hills may be cut down and the valleys filled up to the extent required to obtain a suitable gradient on the most direct line, or the road may be contoured on the hillsides so as to obtain a surface-line of greater length with easier gradients. The second course is in many cases preferable, especially where economy is important; and it may be laid down as a general rule that the expense of deep cuttings should only be incurred where the total rise can be reduced by so doing.

'Where sloping ground occurs it is better to follow the contour

[1] E. Dobson: *Pioneer Engineering*, p. 89.

lines with long stretches of easy gradients, and to flatten the curves, where necessary, by cutting off the spurs, than to set out straight road-lines. These involve either a number of additional culverts, or the breaking up of the road into a succession of short, alternating gradients, than which nothing can be more objectionable.

'(2) *When the route follows the line of a principal valley crossing the main watershed at its head.* The first thing to be done is to ascertain the lowest point of the range to be crossed, and the next step is to ascertain its actual altitude and the distance from the foot of the ascent to the summit of the pass. From these data the gradient can be calculated approximately; and it is to be borne in mind that the actual gradient must be steeper than the calculated gradient, in order to allow for passing through the most favourable ground.' [1]

Mountain Passes. 'These generally come under one of three classes:

'(1) A simple saddle connecting the heads of two valleys.

'(2) A saddle connecting the head of one valley with the side of another.

'(3) A valley between steep hills, leading from a point near the head of one valley to a corresponding point in another.

'The first two cases are generally very simple in treatment, the only question being whether the summit should be cut down or passed over by surface gradients. The latter plan should be adopted where practicable, as it is difficult to keep the slopes of cuttings in repair at high elevations, to say nothing of the risk of a road being blocked by snow-drifts in the cuttings. The third case, however, often requires a great deal of careful study. The ends of the upper valley forming the pass are often blocked by moraines, enclosing peat swamps and deep pools of water, sometimes of sufficient extent to be dignified by the name of lakes. It will be a matter for consideration whether the morasses should be drained or skirted, and whether the moraines should be cut down or passed over. As a general rule it is desirable, at high elevations, to avoid as far as possible both embankments and cuttings and to adopt surface gradients, whenever practicable, although involving a somewhat circuitous route.' [2]

[1] E. Dobson: *Pioneer Engineering*, pp. 75–80.

[2] E. Dobson: *Ibid.*, p. 84.

Subgrade Foundation

A **sound subgrade foundation** is of great importance, and in new countries, or at times in the case of new roads in old countries, failure is due to unsoundness in the subgrade, when soundness might have been obtained by a change in the alignment.

When a preliminary examination has not disclosed the reliability or otherwise of the proposed subgrade, trial pits will be necessary.

Subsoil Drainage. The drainage of the subsoil provides for the removal of any water that may penetrate beneath the road-covering in cuttings and on the more or less level tracts, and is obviously of great importance, especially in the case of waterbound roads. For if the soil is not properly drained, a thaw succeeding frost will break up the road.

On rock, and on siliceous and calcareous soils, there is no great difficulty, and the ordinary side drains in cuttings and open ditches on the more level portions will suffice. But the side drains and ditches must be rather deeper than the greatest depth to which frost is likely to penetrate. In Canada, very deep ditches are necessary so as to drain the subsoil before the frosts set in.

On clay soils in addition to the side drains, transverse **V**-shaped drains are required with the apex away from the direction of the flow, in which salt-glazed drain pipes 2 to 3 inches in diameter are laid from 15 to 18 inches below the centre of the roadway, and connected to the side drains.

Bottoming

This is the lowest section of the road covering and should rest on a solid surface.

The best bottoming for all roads is **cement concrete,** but except for very heavy traffic or for soft places the expense is, as a rule, prohibitive. **Lime concrete,** especially if made with hydraulic lime, natural or artificial (see Chapter X), is sometimes used, and may have a future. Where clay has to be excavated, the clay may be burnt in balls and ground with ordinary lime so as to give the requisite hydraulicity.

Stone bottoming or **soling** is essential for roads carrying heavy traffic. It consists of medium and large blocks laid by hand broad ends downwards, and filled in with smaller pieces and wedged with chips and spalls. It should be well consolidated with heavy rollers, and made up to the proper camber.

Slag, broken brick, or burnt clay are often used for bottoming. The clay should be burnt much harder than when used for hydraulic lime. Chalk is said to make a good bottoming. It can be used over a layer of flints, which are often found in chalk districts.

Geological knowledge comes in with reference to the relation of the subgrade foundation to the bottoming. Where clay subsoil cannot be avoided, it should be blanketed by a layer of some 6 inches of ash, clinker, hard core, or gravel.

A **depth** of 9 inches is commonly specified for the bottoming, but where the subgrade foundation is at all soft, a greater depth up to 15 inches is necessary.

Surface Coating

The enormous improvement effected by modern methods of waterproofing roads has driven waterbound roads out of our towns and main thoroughfares, but owing to their comparative cheapness waterbound roads must, for a long time to come, continue to be used for all classes of roads in many parts of the world, as well as for secondary roads, by-roads, etc., in our own country. But, doubtless, *surface treatment* will come into use more and more for such roads.

Waterbound roads are made with one or more coats of metal, each coat being properly consolidated, and finished with a ' carpet ' of finer metal or gravel (see Section II).

Partially waterproof roads are made by giving some form of *surface treatment* to a waterbound road (see Section II).

Waterproof roads are described in Section III.

SECTION II. WATERBOUND AND PARTIALLY WATERPROOF ROADS

Need for Scientific Knowledge. A knowledge of geology is of great importance, not only as indicated in Section I above, but also in the selection of sites for quarrying stone, and in the scientific study of road materials.

Experience is no doubt very valuable, but this takes time, which is not always available, especially in new countries. Moreover, stone even from the same quarry is apt to differ very much in durability.

Water. The amount of water present at any one time in the air, in the subsoil, and in the crust of a road varies so much that this

question deserves careful attention. Waterproof roads are now largely used in civilised countries. They keep the surface dry and protect the subsoil. But waterbound roads must be adequately drained, though they must not be drained too quickly or the surface will be liable to break up in dry weather. If drained slowly, they will be firmer and less dusty in ordinary weather, and less liable to injury from heavy rains.

In very cold countries, however, it is more important to prevent frost getting into the subsoil, and deep side drains are necessary.

Qualities of Macadam

The essential qualities of a good stone for macadam are: hardness, toughness, durability, and binding or cementitious qualities.

Hardness is the resistance which the stone offers to the displacement of its particles by friction, and varies inversely as the loss in weight by grinding with a standard abrasive agent.

Toughness is that property which admits of the constituent minerals yielding to a small extent without separation of the parts, and enables the stone to resist fracture when struck with a hammer, or by the blows and concussions which obtain on the surface of a road.

Stone for road-metalling purposes may not only be hard, but brittle, and consequently deficient in cohesion or toughness, as in quartz and flint. These crumble under traffic, owing to the hard grains being insufficiently bonded together or mutually attached. This defect, to a certain extent, applies in the case of the intrusive and volcanic rocks, which have a high acid composition.

Durability depends partly on the hardness, cohesion, and structure of the stone, which enables it to resist abrasion, and partly on its power to resist chemical decomposition, and on its mineralogical composition.

Structural characteristics are referred to in Chapter IV. In the special case of road-stones, fineness and evenness of grain are preferable to coarseness, as a rule. Fluxion structure, banding, and a fissile tendency are unfavourable.

Chemical decomposition. The tendency to decompose or 'weather' is referred to in Chapter V, Section IV. In addition to the ordinary weathering action, road materials are often affected by the solvent action of surface-water charged with organic acids and salts.

The chemical stability of different rocks varies greatly. The

effect of traffic on road-stones composed, even partly, of unstable minerals is to cause rapid disintegration.

Mineralogical composition. While the durability of the essential minerals is important, the strength of the matrix and the nature of the accessory minerals are often determining factors.

Binding or Cementitious Properties. This quality depends to a great extent on the toughness of a rock and its resistance to spalling and fracture. Road-stone showing these characteristic features has generally a rough-fractured surface which enables it to retain its position in the road better than a stone having too smooth a surface. Road-metal consolidated by using chips and dust of the same material, especially if the rock is of the more acid varieties of the volcanic and porphyritic groups, is generally deficient in cementitious properties; it therefore becomes necessary to employ binding material of a slightly clayey nature to maintain cohesion.

Physical Tests. Tests can be made to determine the physical properties of hardness, toughness, crushing strength, abrasion, absorption, cementing or binding value, and specific gravity. American practice in this respect is in advance of British practice, and some of the following are taken from those laid down by the American Society of Civil Engineers.

Hardness. The test is made with a 'Dorry' or similar machine, consisting of a revolving disk on which is fed, at a uniform rate, a standard quartz-sand passing a 30- and retained on a 40-mesh sieve. Two cores, each 0·98 inch in diameter, are cut from the material to be tested, and their faces ground off so as to be at right angles to the long axes of the cores. The cores are placed in the holders or dies and weighted so that the entire weight of each core with its holder and added weight is 1250 grammes. Each core is ground in the machine on one face for 1000 revolutions, after which it is reversed and ground on the other face for another 1000 revolutions. The loss of weight of each specimen is determined at the end of each 1000 revolutions, and the average loss in weight is found by the formula: $\text{Hardness} = 20 - \frac{1}{3}W$, where W equals the average loss in grammes per 1000 revolutions.

Toughness. This property is very important, as a stone may be hard but brittle, in which case it is useless as a road-stone. Test-pieces must be cut from freshly grained rock, and must show no signs of incipient fracture due to blasting, etc. They are tested in a 'Page' or other suitable impact machine, and are cut into cores 24 to 25 mm. in diameter and 28 mm. long. The ends are carefully

squared and ground smooth. The test-piece is held on a base or anvil weighing not less than 50 kg., and above it is placed a plunger of 1 kg. weight, its lower end being spherical and hard-tempered. A hammer weighing 2 kg. falls on the plunger from a height of 1 cm. for the first blow, and for each succeeding blow the height is increased by 1 cm. The height of the blow in centimetres at time of failure gives the toughness of the specimen.

The tests for the crushing strength, absorption, etc., and specific gravity of building stones given in Chapter VIII, Section III, are also suitable for road-stones.

Abrasion. The 'Deval' machine consists of one or more cylinders, 20 cm. in diameter and 34 cm. in length, inside. They are mounted at an angle of 30° with the axis of revolution. There should be fifty pieces of stone broken as uniformly as possible, and the total weight should be within 10 grammes of 5 kg. The samples are washed, dried, and weighed and put into the machine, which is given 10,000 revolutions at the rate of 30 to 33 per minute. All pieces retained on a $\frac{1}{16}$-inch mesh sieve are weighed and give the percentage of wear.

Cementing or *Binding value* is ascertained by making briquettes from the stone dust, which are placed under a plunger which is struck by a hammer weighing 1 kg. falling 1 cm. at each blow. The number of blows required to break the briquette is a measure of the cementing value.

Kinds of Macadam

Granite is the best material for road-coverings, and this term, as used by road-makers, includes syenites, diorites, andesites, diabases, and gabbros.

In places where the cost of granite, as above defined, is prohibitive, the best material available locally, or within reasonable distance, must be used. But for an ordinary waterbound road subject to hard wear and not surface treated, the best material is the cheapest in the end.

A road-stone should be hard as well as tough, with an uneven texture, so as to ensure a rough surface. Stone of uniform texture, composed of only one ingredient, is unsuitable for hard wear.

Limestone is unsuitable for this reason, and also because it is too soft and easily worn into dust and mud. See, however, Waterproof Roads, Section III.

Flints, though hard, have a smooth fracture, and consequently do not afford the necessary roughness of surface.

Iron and **Steel slag** are much used in the Midlands and North of England, but make a muddy surface.

Igneous Rocks. *Granites.* Those which are compact and fine-grained, and composed of muscovite and orthoclase, may be taken as reliable material for road-metal. The durability and hardness of granite are the greater the more quartz and hornblende predominate, and the less the quantity of felspar and mica, which are the weaker and more perishable ingredients. Smallness and lustre in the crystals of felspar indicate durability; largeness and dullness the reverse.

Syenite in most cases forms an excellent stone for road-metalling purposes. Like granite, its durability is greater when quartz and hornblende predominate.

Diorites. These rocks are largely used as road-metal, and those having the component minerals fine-grained and compact are satisfactory and durable compared with those of coarse grain, which quickly decompose and form mud in wet weather. Diorites come under the heads of 'Trap Rocks' and 'Greenstones' (*cf.* Chapter VIII, Section I), as do *gabbro* and *diabase*—the latter being fine-grained and the former coarser, while both are suitable for road-metal.

Porphyry is much used for road-metal (see Chapter VIII, Section I).

Basalt and *dolerite* are also known as greenstones, the former being fine-grained whilst the latter is coarser. They are generally hard and durable, and suitable for road-metal.

Andesite. The felted structure of the ground-mass in typical pyroxene-bearing andesites is advantageous to durability, but if the flow-structure is sufficiently pronounced, it is a source of weakness in road-stone.

Metamorphic Rocks. '*Hornfels* vary in structure greatly, and are somewhat brittle: when hornblende is an important ingredient, the rock is preferable to those composed of constituents of a less tough nature.

'*Mica-schist* is used as a road-stone in the West Highlands of Scotland and in Wales, on light-trafficked roads, with good results.

'*Quartzites* are distinctly superior to all other descriptions of rock in the Metamorphic and Sedimentary Groups, as material for road-making. This result is mainly due to the fact that the grains are completely cemented together with quartz; these stones are, however, very brittle.'[1]

[1] Thomas Aitken: *Road-making and Maintenance*, 2nd ed., p. 102.

Sedimentary Rocks. 'Most of the *limestones* have been largely, and are still, employed as road-stone in many counties in England. The durability of these rocks is influenced by their porosity, which varies with the compactness and crystalline texture. The Carboniferous or Mountain limestone is the best of this group of rocks for macadam. When subjected to heavy vehicular traffic this road-stone makes much dust in dry, and mud in wet, weather, the latter being of a very greasy nature. Alternate frost and thaw renders this material practically useless on roads thus affected.'[1]

Sandstones are much used for bottoming roads, but are too soft for metalling.

Laterite for road-metal should be hard, compact, heavy, and of a dark colour. The lighter-coloured laterites, as well as those containing much ochreous clay, should be rejected. Laterite, which approaches hæmatite in quality, is the best material to be used.

Secondary Roads and By-roads

'Besides igneous rock, there are many of the tougher and more durable of other stones which are suitable for any except the heaviest traffic, and others which have special advantages on certain soils.

Limestone. 'Among such stones limestone is the most important. The dust formed on a limestone road is seldom of a very irritating kind, the stones do not cut rubber tyres, and though the glare on white limestone is sometimes rather trying, the gain is, on the whole, with a road which absorbs less heat than others, while the lessened radiation diminishes frost. Limestone wears evenly and smoothly, and yields a cementitious detritus. It is therefore a good weather-resisting material, and on "weather-resisting" roads a fairly soft stone may be quite suitable for light traffic. There is less shifting of material on a limestone road than on most other kinds of similar cost; and shifted material does, as a rule, less damage to the road-crust.

'*Siliceous* limestones have the advantage of producing a less slimy mud than purer or than marly stones, and several useful stones for road purposes lie on the border between sandstones and limestones, the presence of carbonate of lime in considerable quantity in the sandstone having a good effect upon the binding and toughness of the broken stone. Gritstones are usually better than sandstones proper, but are apt to yield a more irritating dust.'

[1] Thomas Aitken: *Road-making and Maintenance*, 2nd ed., p. 102.

'**Flints** are largely used for by-roads in their districts, and are exported a good deal. Though some flints are tougher than others, they are generally too brittle for road metal, and produce irritating dust. They break "unkindly," and the fractures are sharp and bad for car tyres. Unbroken small flints are often suitable for the "shoulders" of a road of a modest class. Water does not rest upon the surface of such a strip, which forms a means of draining the carriage-way without a scour. There is a kind of interlocking between flints of irregular shapes which enables them to sustain traffic to some extent with little disturbance. For the carriage-way proper they should be broken small and well consolidated with a binder, such as a little clay or marl. For a very cheap road flints may be used to top a loamy gravel, shoulders being made of the larger pebbles raked out. For roads of quite an important class flints have some uses, such as giving side support, filling spaces where vehicles occasionally pass, and bottoming or partly filling the cuts to drains.[1]

Gravel. 'The materials commonly known as "gravel" vary from a mass of pebbles by themselves to what is little more than loamy, marly, or sandy matter, with a few pebbles or fragments distributed through them. Pebble beds often yield very good material for by-roads, and the objection to their use on more important roads is often based rather on their shape than their material. Large quartz pebbles are often broken up for road-metal. Successful roads have been made with gravels containing 50 per cent. of pebbles, 30 per cent. of sand, and 20 per cent. of clay; and generally gravels with a proportion of ferruginous clay will bind well together, and, with a top layer of hard stone, or of the larger pebbles well broken, make roads of a fair wear-resistance. With sufficient cohesion in the materials, and the prevention of excessive dryness, combined with the right kind of drainage, gravel roads may be fairly weather-resisting.'[1]

It will, however, be easily understood that for country roads, any hard material that does not soon work up into mud or grind into dust, and that has the advantage of requiring no expensive carriage, will be selected. It is well to remember, in such cases, that sandstone is better than limestone, and hard limestone is better than slate; while basalts and granites are exceedingly good or exceedingly bad, according to the proportion of alkaline earths (especially soda) which they contain.

[1] Reginald Ryves: *Engineering, 1905: Broken Stone Roads.*

Kankar (see Chapter X, 'Indian Limestones') is largely used in Upper India, and makes a good road except for very heavy traffic. It is found a short distance below the ground surface, sometimes in a continuous stratum about 1 to 1½ feet thick, when it is called block kankar, and may even be used for masonry, but more generally in the nodular form. The nodules vary in size, and they and the block kankar should be broken to required size as soon as dug, as the kankar hardens after exposure to the air. The breaking should be so as to allow of the lower layer being made of large pieces and the upper of smaller ones.

Kankar varies much in quality, the inferior kinds containing so much clay as to be almost useless, and the hardest kinds even requiring an admixture of clay to make them bind.

Moorum. This is the chief material used in road-making in the Bombay Presidency, as it is generally obtained close at hand at small cost, and affords the best sort of materials with which to commence a new road.

The term moorum is often applied to almost all descriptions of subsoils which are suited for the surface of a road, by being at all harder than the common earth, and a moorumed road may contain in it different portions of sand, laterite, broken bricks, kankar, yellow earth, or any hard strata, which may be met with below the surface.

The real moorum is probably trap rock in course of disintegration.

Binding Material

Probably the **best binder** for waterbound roads is fine limestone. But the choice of a binder is frequently affected by the kind of stone employed for the macadam. When a stone wears to a slimy mud, sand or grit, or chips of siliceous rock, are better binders than a clayey material; when, however, sand or grit is the chief or sole detritus, clay is a better binder than sand.

On **main roads** clay should never do more than fill the interstices between stones, or stones and chips which are jammed tightly together. On a road which is regularly swept and sometimes watered, more importance may be attached to the binder as a packer, and less to its direct effect upon the traffic. Sometimes more than one kind of binder may be used; for instance, a cheap local material in the lower layer, and a little of just the right material for the stone used as a wearing layer.

It is cheaper and easier to make a road with a good deal of clayey

or marly material than to make it of solid stone with binder crushed in at the surface ; and as the road made with clay consolidates, the superfluous clay may gradually be removed. But such a method is not suitable for main roads with much traffic, on which the camber must be more accurately adjusted, the pieces of stone must be jammed tightly together, and the whole crust so compacted that the area of subsoil on which a wheel rests is as large as possible.

Special binding solutions, such as *rocmac* and *glutrin*, were used to some extent before tar-spraying was introduced. A dressing of *calcium chloride* has been found useful, as it absorbs moisture.

CONSOLIDATION

Many roads are spoilt in the making by the use of too much water and binder during rolling. The macadam should be rolled and re-rolled *dry* till it is thoroughly compacted, and only then should water and binder be added. This is seldom carried out, possibly because it is more tedious and expensive in first cost, but it is well worth while in the long-run.

PARTIALLY WATERPROOF ROADS

Waterbound roads may be given some form of **surface treatment,** which may consist in spraying or painting the surface with *tar*, *bitumen*, or *oil*, and spreading chips or gravel thereon.

A proportion of *rubber* with the tar or bitumen has been experimentally used, and this method may become popular.

Cement grouting is sometimes adopted, but usually costs as much as, if not more than, tar macadam, which is more effective.

SECTION III. WATERPROOF ROADS

Waterproof roads may be made in the following ways :—

Cement concrete, plain or reinforced, with or without a coating of asphalt or other material, dressed with stone chips or gravel.

Tar macadam, bituminous macadam, or macadam with both tar and bitumen.

Asphalt.

CONCRETE ROADS

Bottoming. As a rule the concrete combines in itself both bottoming and surface coating, but on clay or light soils a bottoming of broken brick or stone will often be advisable, or a bottoming of hydraulic lime concrete will prove effective and inexpensive.

Surface Coating. The best *aggregate* is granite or gritstone, with a minimum thickness of 6 inches. An aggregate of broken brick is sometimes used, but should be at least 8 to 9 inches thick. A similar thickness should be given if local stone other than granite or gritstone is used.

Whether one or two *coats* are to be given depends chiefly on the nature of the aggregate. If it is really hard, only one coat may be required, but with a fairly good local aggregate, a first coat of the latter 5 to 6 inches thick, followed by a 2-inch coat of granite or other hard stone, will be suitable.

The usual proportions for cement concrete surface coating are 1–2–4, but these proportions should be varied according to the nature of the aggregate and the thickness of the coat. The percentage of water in the mix should depend on the nature of the bed.

Wearing Surface. New concrete roads are often left with no surface dressing other than a fine coat of sand, but when the surface becomes worn, an asphalt coating is applied and finished with chips or gravel.

Tar, Pitch, Bitumen, and Asphalt

These terms and their limitations are often misunderstood and misapplied, with the result that specifications are so vague as to admit of inferior materials being used and incorrect mixtures adopted. It is most desirable, therefore, to use in all cases the British **Standard Nomenclature,** which is as follows:—

Tar is the matter (freed from water) condensed from the volatile products of the destructive distillation of hydrocarbon matter, whether this be contained in coal, wood, peat, oil, etc.

Pitch is the solid or semi-solid residue from the partial evaporation of tar.

Bitumen is a generic term for a group of hydrocarbon products soluble in carbon disulphide, which either occur in Nature or are obtained by the evaporation of asphaltic oils. The term shall not include residues from paraffin oils or coal-tar products. The commercial materials may be described as bitumen if they contain not less than 98 per cent. of pure bitumen as defined above.

Native bitumen is bitumen found in Nature carrying a variable proportion of mineral matter. The term 'native bitumen' shall not be applied to the residuals from the distillation of asphaltic oils.

Asphalt is a road material consisting of a mixture of bitumen and finely graded mineral matter. The mineral matter may range from an impalpable powder up to material of such a size as will pass through a sieve having square holes of ¼-inch size.

Native or *Rock asphalt* is a rock which has been impregnated by Nature with bitumen.

Additional Definitions. To the above definitions the following may be added :—

Bitumens are subdivided into *Bitumens proper* for the solid type, and *Malthas* for the viscous or semi-fluid types.

Asphalts are subdivided into *Natural* and *Artificial.*

The material that is made artificially from grit or crushed stone, when bonded with tar is known as *tar macadam*; when bonded with bitumen, as *bituminous macadam.*

Bituminous rock. This term is really a synonym for natural or rock asphalt, but is sometimes used to denote a rock in which the percentage of impregnation is comparatively low.

Artificial rock asphalt is prepared in the form of mastic or powder—both being manufactured from the natural rock asphalt after it has been reduced to powder and additional bitumen being added as required.

Rock asphalt powder must not be confused with the natural rock powder—it is made up to a definite specification and used for compressed asphalt tiles, etc.

Rock asphalt mastic usually contains from 14 to 16 per cent. of bitumen.

Mexphalte and *Astecphalte* are proprietary names given to bitumens which are oil residuals. 'They are refined, are not of the right consistency, but have to be fluxed with lighter oils.'[1]

For further information as to tests, fluxes, etc., see the works cited at end of this chapter.

Bitumen and Bituminous compounds are found in Europe in Austria, France, Germany, Hungary, Italy, Russia, Spain—Switzerland and Turkey ; in Asia, in Burma, China, Japan, Persia and Syria ; in Africa, in Egypt and South Africa ; in America, in Argentina, Barbadoes, Canada, Colombia, Cuba, Ecuador, Honduras, Mexico, Peru, Trinidad, United States, and Venezuela.

Many of these deposits consist of native bitumen, whilst others are rock asphalt or bituminous rock. The soft and viscous bitumens

[1] Francis Wood: *Modern Road Construction*, 2nd ed., p. 129. Charles Griffin & Co.

are seldom found pure, but generally impregnate some mineral bed. Pure bitumen is often found in cavities of rocks which are difficult of impregnation, such as the 'ophites' of the Landes, the 'peperites' of Auvergne, the 'syenites' of Cuba, etc.

In Europe, the purest bitumen is found in the Dead Sea, but generally the deposits are bituminous rock or mineral.

Of the *European* deposits of bitumen, mention may be made of those in Albania, Catalonia, Russia, including 'Kir' in the Caucasus, which is formed by the evaporation of naphtha; Tyrol, and Pechelbronn in Germany.

In Europe, the most important deposits of rock impregnated with bitumen are at Limmer and Verwhole in *Germany*; and Lobsann in Alsace; Val de Travers in Switzerland, which is one of the best known; and Ain and Haut-Savoie (Seyssel), Pont du Château, Cortal (Champ des Pois), Colombier des Roys (Dallet), Lempdes (Puy de la Bourière), Lussat, Malintrat, and Chamaliéres, in *France*; at Chieti, Pepoli Lanciano, Venotro, Ponte Corvo, etc., in *Italy*; at Rinazzo in the province of Syracuse, and near Leperino in *Sicily*; and at Maestu in *Spain*, where there is an immense deposit of bituminous rock.

In *Asia*, extensive beds impregnated with a very fluid maltha are found in N. India and Persia.

In *Africa*, bitumen has been found in Algeria.

In *America*, the chief deposits are in the West Indies, where the 'lake' and 'land' bitumen of Trinidad are pre-eminent, and at Bermudez in Venezuela there is a huge deposit; while there are large deposits in Cuba, near Coxitambo in Peru, and in Barbados, where it is known as *Manjak*, and in the Island of San Domingo.

In the continent of N. America bitumen is found in many territories, ranging from Alberta to Texas, and in many forms, such as asphaltic oils, semi-fluid malthas, rubber-like 'wurtzilite' or 'elaterite,' brittle 'grahamite' and 'glance pitch.' Impregnated limestone is found in Texas, and impregnated sandstone in Kentucky, Utah, Missouri, Indian Territory, Texas, and California.

The solid bitumen found in Colorado and Utah is known as 'gilsonite' or 'uintahite.'

Tar and Bituminous Macadams

These consist essentially of macadam impregnated with tar or bitumen, or a mixture of both.

The nature of the aggregate depends on two considerations:

(1) The best results can be obtained by the use of a stone which has about the same wearing capacity as the matrix. (2) A stone which has the greatest affinity for tar or bitumen is preferable to a hard stone such as granite.

Hence limestone, Kentish rag, sandstone, or flaggy stone—all of which are composed of particles of a similar kind—are the best for this purpose. Some engineers prefer *slag* as an aggregate, *e.g.* Mr W. J. Hadfield, author of *Highways and their Maintenance.*

Tar and bituminous macadam are usually finished with a coating of asphalt with a fine aggregate, and may be given a surface-dressing of stone chips or gravel.

Tar may be obtained from coal, wood, peat, gasworks, blast furnaces, coke-ovens, etc.

Pitch (*vide* 'British Standard Nomenclature' above) is obtained from tar. It is, however, as well to note that, strictly speaking, pitch is a bitumen (as defined above) with extraneous matter such as free carbon, residual coke, etc.

For further details regarding the use of tar and pitch for roads, the reader is referred to technical works on the subject.

Bitumen (*cf.* 'British Standard Nomenclature' above). The name is derived from the phrase *Pix tumens*, denoting 'bubbling or fervent pitch.' It may be gaseous, liquid, semi-liquid, or solid.

Bitumen is partly soluble in petroleum naphtha—the soluble portion is known as *petrolene* and the insoluble portion as *asphaltene* (or maltene). Asphaltenes have no binding effect by themselves, but in solution or when mixed with petrolenes give the latter their binding properties and additional stability.

Much petroleum residue is classed as bitumen which contains oily petrolenes unsuitable for road work.

For tests, etc., see the works cited at the end of this chapter and other technical works.

Asphalt Roads

These may be laid with a single coat, or with two coats consisting of a *binder course* of hard aggregate not more than 1½-inch gauge, and a *wearing course* of fine material with bitumen or asphalt. The coat or coats may be laid hot or cold, and there are a considerable number of different processes the description of which is beyond the scope of this book.

SECTION IV. CANAL-MAKING

'In laying down and arranging the general line of a canal, many points have to be considered in addition to those which apply to them in common with roads and railways. One of the most desirable points to be attained is a perfectly **level surface** throughout its whole extent. It is, however, very seldom that the country is so favourable as to allow this to be effected. In most cases it becomes necessary occasionally to alter the level of the surface of the canal, the water being retained at the higher level by gates so placed that the pressure of water against them keeps them closed. It is, however, impossible to prevent a small amount of leakage at the gates, and therefore it becomes necessary to have the means of supplying the upper portion of the canal with water, to compensate for that which thus escapes, as well as that which is necessary to pass vessels from the higher to the lower level. In addition to these two causes of loss, a further waste is occasioned by the evaporation from its surface, and the absorption of the water by the ground through which it flows (*cf.* Chapter VII, Section I).

'It is, therefore, an object of considerable importance in the arrangement of a canal to obtain some **natural feeder** (as it is termed) for the supply of the water thus lost, which object is usually attained by diverting some of the smaller natural rivers or streams, and leading as much of their waters as may be required to supply the highest (technically called the *summit*) level of the canal, for that being properly supplied, the lower levels will be fed by the water which escapes from the upper.

'Before forming a canal, the **strata through which it will pass** should be carefully examined, more especially with reference to its powers of retaining water, that is, of not absorbing it. Many soils, such as clean sand, or gravel, would carry off the water so rapidly as soon to drain the canal, and therefore such strata should, if possible, be avoided. Where, however, it is impossible to do so, the canal may be made watertight by lining its sides and bottom with *puddled* clay, which consists of good clay, thoroughly well-beaten up with water, or *tempered*, and then mixed with a certain proportion of gravel, sand, or chalk. Pure clay by itself would not answer, because if at any time the water in the canal sunk below its ordinary level, the upper part of the puddle, becoming dry, would crack; and when the water again rose it would escape

through these cracks, which by its action would be gradually enlarged until the puddle was rendered useless.' [1]

When a canal traverses a valley, it should if possible be located on the side-slopes, where the soil is firmer and not so porous, but if it must be treated in the valley, its banks should be raised above the maximum flood-level.

Leakage. The importance of geological knowledge in canal-making was long ago recognised, and was applied by Mr W. Smith, in 1811, in a very successful manner. About that time many canals were being cut in the west of England, and these, crossing the oolitic hills, were found to be particularly liable to accidents of leakage, being cut through open-jointed, and sometimes cavernous, rocks, alternating with watertight clays. In the passage across the former rocks, and more especially when the summit-level of the canal occurs in them, the water escapes almost as fast as it enters, and all the skill of the engineer in puddling and making an artificial bed is sometimes exerted in vain, and cannot prevent great and ruinous loss. But the existence of open joints and caverns is by no means the only, nor indeed is it the greatest, source of injury, for innumerable small faults or slides traverse the country and confuse the natural direction of the springs, rendering them short in their courses and uncertain and temporary in their flow, weakening by their irregular pressure every defence that may be opposed to them, and causing leaks which let through a portion of the water contained in that level of the canal.

The **general remedy** for all these evils was understood by Mr Smith and proposed by him for adoption. It is 'the entire interception of all the springs which rise from a level above the canal, and pass below it through natural fissures and cavities. This is a process requiring great skill and extensive experience; some of the springs, for instance, which it is most important to intercept, come not to the surface at all in the ground above the canal, but flowing naturally below the surface through shaken or faulty ground, or along masses of displaced rock which extend in long ribs from the brows down into the vale, emerge or attempt to emerge in the banks of the canal; there no ordinary surface-draining will reach, and none but a draining-engineer, well versed in the knowledge of strata, can successfully cope with such mysterious enemies. But Mr Smith, confident in his great experience, not only proposed, by a general system of subterraneous excavation, to intercept all these

[1] H. Law, C.E.: *The Rudiments of Civil Engineering.*

springs and destroy their power to injure the canal, but further to regulate and equalise their discharge so as to render them a positive benefit. This he would have accomplished by penning up the water in particular natural areas, or pounds, which really exist between lines of fault in most districts, or between certain ridges of clay ("horses") which interrupt the continuity of the rock, and divide the subterranean water-fields into limited districts, separately manageable for the advantage of man by the skilful adaptation of science.' [1]

[1] Phillip's *Life of William Smith*, p. 69.

BIBLIOGRAPHY

(In addition to works quoted)

CAREY, A. E.: *The Making of Highroads.*

DANBY, ARTHUR: *National Rock Asphalts.*

HADFIELD, W. S.: *Highways and their Maintenance.*

PAUL, Major E. M., R.E.: *Manual of Road Construction and Maintenance.*

ROYAL MINIKIN, R. C.: *Practical River and Canal Engineering.*

CHAPTER XII

RIVERS

THE work done by running water has been briefly considered in Chapter I, Section I, but, to enable the engineer to fully understand the geological action of rivers, a certain amount of knowledge of hydraulic laws is essential.

In fact, the geologist must be acquainted with the principles of hydraulics to enable him to trace the action of rivers, whilst the hydraulic engineer must have more than a mere smattering of geological knowledge if he is to be successful in his undertakings.

SECTION I. CONDITIONS OF FLOW

To enable the engineer to grapple successfully with River Improvement Schemes (*vide* Section III) he must have some knowledge of

(1) The physiographic conditions affecting the flow, *e.g.* the formation of alluvial terraces and plains, and the effects of forests, waterfalls, and rapids.
(2) The principles governing the motion of water in rivers.
(3) The transporting power of water.
(4) The conditions governing fluctuation of flow.

PHYSIOGRAPHIC CONDITIONS

Physical Characteristics of Rivers. A *river* may be defined as the main course through which the run-off from a river basin is borne to the sea; or the line of least resistance to the discharge of the rainfall. Rainfall is referred to in Chapter VII, Section I.

The regime of a river may be defined as the integration of all the forces which maintain the river in the form in which it exists.

The phases of action governing the regime of rivers are erosion, transport, equilibrium, and deposit. Erosion and transport are referred to in Chapter I, Section I. Erosion takes place in the higher and more torrential portion; material is transported to the

lower reaches, and is deposited to form the alluvial terraces and plains mentioned below, with the result that equilibrium is maintained.

Equilibrium does not mean that there are any parts of the river which are not affected by erosion, transport, and deposition, but denotes that there are places in the river where erosion is equalised by deposit.

The *present development of rivers* is due to the work of ages, but in that part of the globe which was affected by the Glacial Period, it is probable that rivers attained their chief characteristics at the end of that period, when the torrents caused by the melting of glaciers and ice-sheets poured over the land and cut deep channels to the sea.

The vast deposits to be found in the principal *estuaries* were probably laid down at that time. In those early times the gradient must have been greater, the velocity of the water correspondingly increased, and the size of the streams much larger, as evidenced by the remains of *river terraces* (*cf.* Chapter I, Section I).

Probably the regime of rivers became established at the end of the Glacial Period when the forces of erosion were balanced by the resistance of the soil, and the struggle between the tidal water and the torrential streams resulted in equilibrium.

The flow of water in rivers is referred to in Chapter VII, Section IV. Every river presents a different problem, but in general terms the flow of water may be said to depend on—

(*a*) The physiographical and geological features of the region through which the river passes.

(*b*) The formation of the river bed.

(*c*) The quantity of water discharged in a given time in wet and dry seasons.

River Valleys. While the nature of the strata through which a river flows has an effect on its discharge, it also affects the number and size of the tributaries of the river, and also the shape of the river valley.

If the strata were only affected by the flow of water in the river, the bed of a river would be deep and narrow, but the effect of the erosive agents, especially rain, referred to in Chapter I, Section I, is to wear away the river banks. Gullies become streamlets, these unite into streams and streams become tributaries, and all carry away matter from the banks of the river. The rapidity of this

process of denudation depends on the nature of the strata, and it is accentuated towards the river mouth, where the lowlands are usually composed of sedimentary strata which are easily denuded. The meanderings of the lower course of a river are due to obstructions round which the river twists its way.

Such valleys are *valleys of excavation*. Other valleys are caused by compression of the earth's crust, *e.g.* River Meuse near Charleville; or by faulting, when they are called *rift valleys*, as River Rhine between the Vosges and the Black Forest.

Upper and Lower Portions of Rivers. Rivers may be divided theoretically into an upper portion or headwaters and branch streams which are not navigable, and a lower or navigable portion known as the main river. The river basin or drainage area is necessarily bounded by high ground, and the headwaters of large rivers take their origin from mountain torrents.

River Basins. The basin of a river is a tract of country bounded by an encircling ridge, on the inner slopes of which the rainfall flows down into the river, whereas rain falling on the outer slopes falls into other basins. River basins or drainage areas vary greatly in extent according to the configuration of the country, and the distance between the source or sources and the outlet of the river.

Fall of Rivers. The rate of flow of rivers depends chiefly on their fall and the amount of friction against their beds and sides. If two rivers of different sizes have the same fall, the larger one will have the quicker flow, since its retardation by friction will be less than that of the smaller one. The fall of a river is generally quickest near its source, which is usually in high ground, and gradually becomes less.

Action of Mountain Torrents. Under the action of the various agencies of disintegration, the mountain ridges are constantly yielding great supplies of debris to the torrents which score their sides. The greater part of the detritus to be found in the beds of these mountain torrents is due to the action of gravity on the steep slopes of the mountains. Not only is a considerable amount of material furnished from time to time by the action of avalanches, but all the rock fragments lying on the slopes, frequently mixed with soil and forming masses of considerable size, are slowly creeping towards the torrent beds under the action of frost, snow, and rain, aided by gravitation. However slow the action, so long as there is a sufficient store lying on or near the surface, the stream beds will

be kept supplied. In places, however, where the supply of store is insufficient, the torrents eat into their beds and make their slopes steeper, with the result that the supply of material is accelerated. In this manner the supply of rock fragments, etc., to the mountain torrents is constantly maintained.

In times of drought the torrents are reduced to rivulets of clear water, but under the action of heavy rain they are filled with water turbid with sediment due to the clashing of the rock fragments and pebbles.

At the foot of the mountain or point where the slope becomes less steep, a considerable amount of sediment is deposited in the shape of an *alluvial fan* (*cf.* Chapter I, Section I).

River Terraces. Further down where several torrents unite to form the headwaters of a river, each flood deposits some of the larger stones which form the beginning of a *river terrace*, the interstices between these stones being gradually filled by smaller ones and the whole terrace becoming consolidated by vegetation.

At this point in its course the slope of the river is too great for sufficient deposition to take place in its bed to counteract the eroding action of the moving load of sediment and detritus; hence the bed becomes lower, and as the terraces are only formed at high-flood level, they are gradually left high and dry—fresh terraces being formed further down.

Alluvial Plains. Further down the river where the slope becomes so little that deposition takes place in the bed, each successive flood deposits sediment over a wide expanse on each side of the river, and at the same time the bed level is raised. This process results in a continued deposition of silt on the expanse beside the river until *alluvial* plains, often of great thickness, are formed.

The formation of these alluvial plains is accelerated towards the lowest part of a river's course, where the bed is so flat that the course becomes very undulating, and thus a still wider expanse is opened up for the deposition of alluvium.

The effect is greatest near the river's mouth, where the combined action of river and sea forms swamps which unaided may eventually become dry land, or may require the assistance of the engineer to drain and protect them (*cf.* Chapter XIV).

The materials which form these alluvial lands grow finer and finer the nearer they are to the river's mouth. This is of course due to the fact that the heavier fragments are deposited as soon as the current begins to slacken.

Undulations. The undulations which are so common in the flatter or lower portion of the course of a stream or river are largely due to the oscillations of the current induced by obstructions in the path of the stream. For example, each tributary which joins the main channel, as a rule, has a steeper bed and swifter current than the main stream. Consequently the silt carried by its waters is checked on reaching the main and slower stream, and a mass of pebbles, etc., is deposited as a sort of bar. This bar when well established deflects the main current to the opposite bank, whence it is again deflected to a point lower down the river. Thus an oscillating motion is produced which tends to induce undulations in the course of the river.

Action of Water-loving Trees. The tendency to form undulations is to some extent counterbalanced by the action of water-loving trees, which find a lodgment on the incipient river terraces and with their roots and branches entangle the sediment and form a barrier or fence to the stream.

Effect of Forests. The valleys of most rivers were originally covered with forests, and while many of these have been cleared away by the hand of man, enough still remain to illustrate their beneficial effect on the conservation of water.

For in all forests, whether they consist of the giant growths of the tropics, the stunted woods near the poles, or the intermediate growths of more temperate climes, beneath the branches and above the soil there is a dense mat or sponge of vegetation, varying in thickness from a few inches to a couple of feet. This sponge acts as a reservoir, storing up the rain-water and yielding it but slowly to the brooks. Moreover, the streams and rivulets of the forest are often dammed by fallen branches, and pools are formed which add to the storage capacity of this natural reservoir.

Where the forests have been cleared or have failed to implant themselves owing to the stoniness of the ground, the run-off of water is greatly accelerated and floods are apt to occur, the river channel is enlarged, and the amount of silt carried off is enormously increased. Hence forests have a very important influence on the activities of rivers.

Effect of Waterfalls and Rapids. These may be due to the presence of veins or dykes in the bed of a river. If the vein or dyke material is softer than the bank it will not obstruct the flow; but if it is harder it forms an obstacle which is exceedingly slowly surmounted, and generally takes the form of a cataract or rapids.

Very frequently waterfalls are due to the presence in the bed of a layer of hard rock dipping against the flow. The face of the waterfall thus formed is gradually eaten away and the full retreat upstream gradually becomes lower in height. Such a retreating waterfall exercises a considerable influence on the conditions of flow of a river, for as it is cut back and reduced in height, the rate of erosion in the valley above it is increased and a larger area is influenced.

Motion of Water in Rivers

Rotary Motion. In flowing water the whole volume does not move forward in one mass, as is the case with a solid body, but every individual particle is in motion. As the volume moves forward, these particles roll round one another in orbits varying in dimensions according to the section of the stream, and each particle is deflected from its course by the difference of level of the surface and irregularities of the bed.

The diameter of each orbit is governed by the distance from the surface of the water to the bottom of the channel and the distance between the sides. In shallow streams the particles are continually circulating in a number of small orbits, rolling round and amongst one another in all directions, according as they are diverted by contact with the sides and the bottom. In deeper streams the orbits are larger, and the disturbing agents fewer in proportion. Thus, with the same velocity the disturbance to the free flow of the particles decreases as the depth and width of the stream increases, and the diameter of the orbits consequently becomes greater.

In other words, the further the centre of the stream is from the retarding medium, the less is the effect of this disturbing rotary motion. This is the cause why a deep stream has a less eroding effect than a shallow one, and why, as the hydraulic mean depth is increased, the velocity also increases.

The tendency of the particles is to move in a curved or rotary path in which the whole mass of the water participates. This rotary motion has a scouring action on the sides of the channel, and tends to scoop out holes whereby the curved motion of the particles is increased, the filaments of water are driven out of the straight path and reflected on to the opposite bank, and so a series of curves is set up.

The existence of the deep pools which are found in the beds of rivers, the curved motion which a stream assumes, and its power

to transport material of heavier specific gravity than itself, are due to this upward and rotary action of the particles of water.

A large volume of water once in motion maintains its flow with a very slight surface inclination.

Retarding Force. 'If, owing to the action of gravity, water continued to flow in a river with no resistance, it would be subject to a constantly accelerating force, but as its motion over any given length is uniform, there must be also a retarding force. This retarding force is due to the friction of the particles of the water against the sides and bottoms, to the adhesion of the particles of the fluid, to variations in the head and irregularities in the form of the channel causing disturbance to the motion and a loss of living force from the particles being reflected in currents contrary to the general direction of motion, and to turbidity of the water.' [1]

Velocity. 'As rivers increase in size the proportion of the retarding to the accelerating force continually diminishes, and they therefore require a less rate of inclination to produce the same velocity.

'Where the flow of water in a channel is uniform, the same quantity of water will be discharged at the lower end of any given length as enters at the upper end ; consequently, the same quantity of water must pass each transverse section per second, the velocity of the current increasing where the area is diminished and decreasing where it is enlarged.

'The *velocity of a stream* is not uniform throughout the whole section. The contact of the particles with the sides and bottom of the channel retards the velocity of the water immediately adjacent, and as the particles are reflected they transmit this retardation to the more distant particles, the particles nearest the rubbing surface being most affected, and each in succession being less influenced, and the retardation decreasing towards the part most distant from the bottom and the sides being at a maximum at the former point and a minimum at the latter. The point of maximum velocity is found to be on a vertical line through the deepest part of the channel and a little below the surface.

'There exists a point where the velocity of the filaments of the water is at a mean of the whole depth. This point varies with the depth and other conditions of the river.

'Generally, the *mean velocity* may be taken at 85 per cent. of the maximum, and its position at the centre, or in deep rivers, at 0·45 of the depth measured from the surface.

[1] W. H. Wheeler: *Tidal Rivers*, p. 47.

'The point of *maximum velocity* is generally a little below the surface on the vertical line passing through the deepest part of the river, the water on the immediate surface being retarded by the friction with the atmosphere.

'The *minimum velocity* is at the bottom, and its proportion to the maximum velocity will be affected to a large extent by the quantity of sediment that is being carried and the depth of the stream.

'Generally, it may be taken that the *bottom velocity* varies from about 75 per cent. of the surface velocity for rivers of depths of about 5 feet, to 50 per cent. for three times this depth, and 66 per cent. for large rivers.

'In these proportions for maximum velocity no account has been taken of the action of the *wind*. Gales have a considerable influence in retarding or increasing the surface, and proportionately the whole velocity. However, observations have shown that the effect of wind on a river (exclusive of tidal causes) does not reach beyond mid-depth.' [1]

Contour. 'The contour of rivers in their natural condition is never found to be regular, either horizontally or vertically. The course of the river, whether tidal or fresh, consists of a series of curves, and a straight reach of any length is very exceptional. The bed also consists of a series of pools and shallows, which maintain their shape and position without change, although the conditions of the flowing water are continually varying, at one time running with great depth and velocity, and carrying along large quantities of solid material, and at other times running with low velocity and at less depth. Temporary alterations may occasionally occur, and a river may change its course; but where the course remains unaltered the contour of the bed will be found to remain materially unaltered. Without an investigation of the cause of this, it would seem natural that the heavy material carried by the water in suspension would be deposited in the pools, and that they would become filled up, and the bed raised throughout, in the same manner as occurs at the mouth of large tideless rivers. After the contour of a river has once been determined, an equilibrium is set up between the erosive action of the water and the resistance of the material of which the bed is composed, and, this equilibrium being once established, the pools are maintained by the rotary action of the flowing water.' [2]

[1] W. H. Wheeler: *Tidal Rivers*, p. 48.

[2] W. H. Wheeler: *Ibid.*, pp. 52–53.

Dynamic Action. 'In flowing water, in addition to the static force which at the same depths presses against the sides and bottom of the channel equally in all directions, there is also a dynamic force depending on the velocity. If the direction of a stream be changed, the particles of water are impelled against the side of the channel, which presents an obstacle to the original line of direction by this dynamic action. The force thus brought into play is absorbed chiefly either in cutting and carrying away the material of which the bank is composed, or, when a state of equilibrium has been reached and the bank is sufficiently tenacious to withstand the impact, in heaping up the water and creating a greater head. In all curves there is, therefore, a radial dynamic action from the convex towards and on to the concave side, causing currents in that direction, which tend to deepen the channel both horizontally and vertically; or else to increase the velocity and raise the surface of the water on the concave side, and to shoal and decrease it on the convex side.

'A channel which has once attained a state of equilibrium is prevented from being further eroded at the curved portions owing to the varying action of the particles of water as they pass round the curve. When water which is moving along a straight channel comes to a part that is curved, the particles of water which are nearest to the concave side are the first to come in contact with the curved side of the channel, and are thus the first to be deflected from their course. The particles next to these, being later, will collide with those previously deflected, and a similar action will take place as each parallel series arrives. The consequence is that the full force of the water, instead of acting directly on to the hollow side of the bank and eroding it, will be gradually cushioned by that part of the stream which has already impinged on it. Even in a sandy estuary, if a deep trough be once scoured out, the reaction of the tidal currents flowing up and down and impinging against the sides and bottom will create an eddying or boring action which maintains the trough at its greatest depth and prevents deposit. It is due to this action that the deep pools are maintained, such as the Sloyne in the Mersey, Lune Deeps in the Irish Sea, Lynn Well in the Wash, and the steep mounds of sand with deeps on each side which exist as bars at the mouths of some tidal rivers'[1] (see *Bars at the Mouth of Rivers*, Section II below).

[1] W. H. Wheeler: *Tidal Rivers*, pp. 54–55.

The Transporting Power of Water

Transport of Material. 'All rivers during land floods are charged with a large quantity of alluvial matter which is carried away in suspension, and their turbid condition then testifies to the work that is being done in the transport of material. This detritus is the result of the disintegrating effect of frost and rains, which break up and loosen the soil sufficiently to allow of its being washed by the rain into the river (see Chapter I). On reaching the channel of the stream it becomes thoroughly mixed with the water, and is carried along in suspension. When this material reaches a tidal estuary, it is transported over the sands and deposited near the banks during the time of slack tide, where, owing to the shallow depth, there is little or no scour, causing salt marshes to accrete; or else it is carried out by the ebb current and deposited in the sea.'[1]

Erosion. Water frequently passes along the bed over which it is flowing without exercising the erosive effect due to the velocity at which it is running. A very slight cause may change part of this velocity into erosive energy. A slight obstruction placed in the bed of a sandy channel will cause erosion, and the scouring of a pool where previously the water had passed over without any effect. The deep pools always to be found at concave bends are instances of the development of this power.

'At certain velocities water has an eroding as well as a transporting power. Under normal conditions the sectional area of a river is sufficient to allow of a velocity slow enough to prevent erosion, and the natural bed of the river remains in a state of stability. If, however, the velocity is sufficiently increased, or any agency comes into play that disturbs the material composing the bed or banks, the transporting power of the water then carries away the soil, and the sectional area becomes enlarged. In the same way detritus brought down at one time and deposited in a channel may be transported away in floods when the velocity is sufficient to erode and stir it up. Thus, also, tidal currents may flow over sands without disturbing or removing them, but if these sands are broken up by wind or wave action, the sand may be transported by the tidal current into the rivers. Shingle beaches are only found where there is a considerable rise of tide and sufficient wave force is generated to erode the cliffs.

'If a stream is loaded to its full carrying capacity it will not

[1] W. H. Wheeler: *Tidal Rivers*, p. 59.

take a greater burden, but flows against the banks and over its bed without eroding them. If, however, it is not over-burdened, and the velocity is sufficient to erode, it will pick up material from the soil over which it passes.' [1]

'The **quantity of material** carried in suspension varies very considerably. In some rivers upwards of 2 per cent. in weight of the total volume of water passing along the channel consists of solid matter.

'Taking the specific gravity of water as 1, the relative weight of coarse river-sand is 1·88; fine sand, 1·52; clay, 1·90; alluvial matter from 1·92 to 2·72. A cubic foot of water weighs 62·5 lb.; of coarse sand, 117·5 lb.; fine sand, 95 lb.; clay, 118·75 lb.; alluvial matter, 120 to 170 lb.; silt, 103 lb.' [2]

Motion of Particles of Matter in Suspension. 'The matter to be transported, being much heavier than the water, will pass from a state of suspension to that of deposit when the water in which it is contained ceases to be in motion. A solid particle, being of greater density than the water, is continually tending to sink, the time occupied being proportionate to its size and specific gravity. The particles of water in running streams have, however, a considerable upward motion which is sufficient to counteract the downward tendency of the solid particles. Thus particles of considerable size may remain in suspension for long distances, while the finer particles may be altogether prevented from sinking. The motion of water in running streams is never uniform, and the relative position of the suspended particles is constantly being changed. The direction of the particles is altered by the varying form of the bottom and sides, by impediments met with on its course, and by the varying velocity of the whole mass due to the friction of the sides and bottom, and of the individual particles of water. Continual eddies and whirlpools are constantly being generated, by which a rotary motion is given to the water. The particles of matter in suspension are carried forward by the velocity of the current, and thrown upwards by the eddies, and thus kept from sinking to the bottom. The bed of a river is rarely regular, but consists of a series of pools and shoals, which have the effect of continually altering the direction of the particles of water. Even where the bed approaches to a level surface it frequently contains a series of ridges, composed of the deposit in transit. These ridges have almost invariably a gentle

[1] W. H. Wheeler: *Tidal Rivers*, pp. 59–60.
[2] W. H. Wheeler: *Ibid.*, pp. 61–62.

slope on the upper side, with a more vertical inclination on the downstream side. Even where the material is sand, the downstream side often presents an almost vertical face, over which the moving particles are rolled. These ridges are constantly altering their form, due to the changing size of the particles rolled along, a single pebble often altering the whole shape of the moving detritus.' [1]

Effect of Alteration in Dimensions of Channel. 'If the velocity of the stream be checked by a widening of the channel, the motion of the water becomes less disturbed, and a portion of the matter in suspension is deposited, the quantity depending on the variation in the velocity of the current. This deposit reduces the area of the channel, and tends to restore the normal velocity. A slight retardation of the current, however, does not necessarily produce a deposit. Increase in depth does not cause deposit in the way that increase of width does. The particles of water in the latter case, descending on one side of the deep and rising on the other, cause a rotary or centrifugal motion in the hollow; the particles of matter brought into the depression are rolled round and directed upwards, and ultimately carried off by the film of water moving above the surface of the pit.' [2]

Proportion of Deposit carried. 'When the water is highly charged with deposit, the greater amount will be found at the bottom and the least at the surface. When it is undercharged, the distribution is more general, the amount at any point being determined by the greater or less disturbance of the particles due to eddies and whirlpools. In the Rhone delta, where the water was very highly charged, the proportion was found to be as 100 at the surface to 188 at the bottom. In the Mississippi, in its ordinary condition, the proportion was only 147 to 188. In a sandy estuary, where the water was much undercharged, the author found the proportion to vary as 8 to 14 and 12 to 28.

'The power of water to transport solid matter depends on the velocity—modified by the depth—which governs the transporting power, in two ways: one certain, when, the quantity of water being constant, the amount of material carried will vary directly as the velocity, and as affected by the time that gravity has to act on the particles while travelling a given distance; the other uncertain, and due to the increase of eddies and whirling motions

[1] W. H. Wheeler: *Tidal Rivers*, pp. 62–63.
[2] W. H. Wheeler: *Ibid.*, p. 63.

set up by the increased momentum of the stream. With regard to the first, if a given quantity of water carries a given quantity of material in suspension, it is obvious that by increasing the pace throughout the whole of the channel the quantity of material carried must also be increased. It is, however, impossible to lay down any rule for the second factor, as it must depend on the contour of the channel and the means for setting up the whirling or rotary motion that keeps the particles in suspension.

'The weight of sand and pebbles, when immersed in water, being only about half their weight in air, these materials are more easily transported by currents of moderate velocity. Sand or pebbles lying on the bottom of a river present an obstacle to the free motion of the particles of water and check their momentum. They are therefore acted on by the dynamic force of the flowing current in addition to the transporting power due to the velocity alone. It is to this cause that pebbles and shingle are moved along a beach by tidal currents of small velocity, and when aided by the disturbance caused by waves, stones of very considerable size are brought from deep water and left stranded on the shore. The momentum contained in the deep water of the sea, due to the tides aided by the current acting on heavy bodies in a partial state of flotation, carries these along and lands them in a position from which the returning wave has not power to move them.

'It has been shown that the particles of water of which a running stream consists are continually rolling round one another in circular orbits, and that the size of these circles depends on the depth of the stream. The deeper and wider the stream the less the rotary motion is impeded. The smaller the diameter of the orbits described by the particles the more disturbed is the condition of the water and of the particles of solid materials which it contains, and therefore the greater the ability of the water to retain these in suspension, and the more the energy expended in rubbing and eroding the sides and bottom of the channel. The larger also the diameter of the circle through which the particles move the more easily they will glide over the surface, and the shallower the water the more direct, frequent, and effective will be their impulse. The greater agitation in which shallow water is kept increases its capacity to hold matter in suspension and to erode its bed. The strength of the stream is absorbed proportionally in this action, and the velocity accordingly diminished. This is no doubt the cause why shallow streams frequently erode the soil of their beds and banks, while deep water

passes on over the same kind of soil without exercising the same effect.' [1]

'The **material transported** by rivers consists either of alluvial matter, clay, sand, or shingle. The first two, owing to the fineness of the particles, are easily transported in a state of suspension. When sand is disturbed, a certain portion, consisting of the very finest particles, is carried away in suspension, but all particles sufficiently large to be visibly angular, as also shingle, require a greater velocity of the current to move them, and their transport is effected by being rolled along the bottom. Although clay will not yield to such a velocity as generally prevails in navigable rivers, if it be disintegrated the particles easily mix with the water and are carried away. Mr Wheeler has found, as the result of observation and experiment, that the most effective results may be obtained by mechanical disintegration and mixing from warp or alluvial deposits, then from clay, and the least effect is obtained from sand.

'The quantity carried in suspension at a given velocity is not wholly in proportion to the specific gravity of the material, but depends more on the fineness of the particles. Even in still water it will be found that the relative time occupied in settling does not vary as the specific gravity of the materials.' [2]

Fluctuations in Flow

Amount of Rainfall. The quantity of rain is referred to in Chapter VII, Section I. In the case of a large river the amount of rainfall will often vary in the different portions of the drainage area; *e.g.* the rainfall affecting the headwaters, and branch streams of the upper portion of the river, may be heavy, while that of the drainage area of the main portion of the stream may be but light, and *vice versa*. Again, the rainfall over the whole drainage area of headwaters, branches, and main river may be heavy, when floods are likely to occur if no controlling arrangements exist.

In cold climates the *melting snows* contribute their accumulated deposits when a thaw sets in, and this effect is greatly increased if accompanied by rain.

Amount of Run-off. This is accelerated by frozen, saturated, or hard ground, retarded by accumulation in lakes, marshes, swamps, or forest land, retarded or diminished by percolation into the ground, and diminished by evaporation and transpiration losses.

[1] W. H. Wheeler: *Tidal Rivers*, pp. 63–65.

[2] W. H. Wheeler: *Ibid.*, p. 66.

Percolation in the ground depends upon the character of the drainage area. Drainage areas are referred to in some detail in Chapter VII, Section V, but the following points are of special importance as regards rivers:—

(*a*) Topographic character.
(*b*) Nature and condition of the soil covering.
(*c*) Geological character.

Topographic character. The slope of the surface is the principal characteristic. A steep slope naturally affords the best opportunity for a large run-off, whereas a slight surface slope retards the rate of run-off, and, moreover, is usually characterised by swamps, marshes, and lakes which hold up the water and afford facilities for evaporation.

Nature and condition of the soil covering. These are often of considerable importance. Grass exercises a retarding effect on the run-off by delaying the movement of water over its surface and preventing erosion; moreover, its close woven mat of roots retards percolation. The dense mass of litter and humus in forest lands assists percolation by absorbing a large amount of water, and retards the run-off by preserving the surface from erosion.

The physical condition of the soil also has a considerable effect, *e.g.* hard and frozen ground facilitates run-off and saturated ground impedes percolation. Cultivated land assists percolation, the surface being broken by the plough and the roots of the crops opening up the lower layers of the soil.

Geological character. The nature of the soil covering has been referred to above, and the most important point for consideration is the absorptive properties of the underlying soil and rocks. The capacity of rocks for water is described in Chapter VII, Section II. The nature of the soils and subsoils is described in Chapter XV, and it will suffice here to state that the soil has an enormous capacity for absorbing water, and this capacity depends upon the amount of free space between the particles of the soil, which generally amounts to between 30 and 50 per cent. of the volume of the soil, and is greatly affected by the amount of aeration of which the soil is capable. The most important feature, however, is the structural character of the underlying rocks. If the rocks are jointed and fissured or faulted, channels are soon formed through the soil and the water passes downwards very rapidly.

Evaporation and transpiration losses, or absorption by vegeta-

tion, also greatly affect the run-off. These are referred to in Chapter VII, Section I.

SECTION II. TIDAL RIVERS

THE PHYSICAL CONDITION OF TIDAL RIVERS

Tidal rivers may be divided into three parts:

1. The freshwater or non-tidal portion.

2. The part within the coast-line confined within limited boundaries, through which the tide ebbs and flows.

3. The estuary, or the part where the coast-line opens out, leaving a wide mouth or bay.

'There are two **sources** from which the water flowing in a river is derived, distinguished respectively as **tidal** and **fresh water.**

'The *tidal water* enters at the lower end, and is derived from the tidal wave of the ocean, which, as its crest passes the mouth of the river or its estuary, raises the level of the water during a period of a little over six hours, filling the tidal basin and causing a run of water up the river; during a similar period, as the trough of the tidal wave passes the estuary, the process is reversed. The supply of tidal water is thus constant, the same quantity passing out of the estuary on the ebb as entered during the flood.

'The tidal motion continues as a wave so long as the depth of water in the low-water channel is sufficient for its generation, but is converted into a current as the depth shoals. This supply of tidal water from the sea has enabled many rivers to be used for navigation which otherwise would not have had the necessary depth of water.

Fresh water. 'The water poured in at the upper end of a river also comes from the sea, but by a different process. This is due to the evaporation caused by the sun, the vapour formed being collected into clouds, condensed again, and in the form of rain falling on the land, and is then collected into the brooks and rivulets which feed the rivers.

'The supply of fresh water, therefore, is limited, variable, and intermittent. This fresh water only travels in one direction. Obeying the law of gravity, it ever continues a constantly downward course, except during the time it is headed back by the tide, until it reaches the lowest point attainable, that is, the trough of the tidal wave.

'In the middle zone of the river, between the purely tidal and the fresh water, the currents assume the oscillating motion due to tidal influence. The current alternately flows both ways, being driven back and raised up during the flood tide, and running down and its level depressed during the ebb. Under certain conditions the action due to the tide may be simply a raising of the level without a reversal of the current.'[1]

Agents of Maintenance. 'There are two principal agents always at work in tidal rivers, one tending to shoal and deteriorate the channel, the other to maintain and deepen it.

'The agencies which *tend to shoal* the channel are the transporting power of the fresh water, which brings detritus down from the upper reaches; the winds and waves, which erode the cliffs and banks; and the currents which disturb the sand-beds in the estuary. The material thus brought into the channel, if left at rest, rapidly subsides in the lower part and raises its bed.

'The continual oscillation of the water due to the tides is the chief agent which keeps the detritus in motion and prevents its deposit. The current of the fresh water, always flowing in one direction, is the chief agent of transport which carries the material away out of the channel to the sea. Its capacity to transport the solid matter continues in a diminishing ratio until the termination of its course. As it approaches the tidal portion of the channel, the conditions of flow become so altered that the tendency to deposit is greater than the transporting force.

'In a tidal river this solid matter is kept in movement by the oscillating action of the tides, until it is finally carried out to sea or deposited on the shores of the estuary, where it settles and forms the salt marshes to be found on the coast.

'In non-tidal rivers, as the current slackens on approaching the sea, the material settles at its mouth and forms deltas.

'The ever-continuous motion of the water in tidal rivers, and the constant reversal of the direction of flow, therefore, give these rivers a great advantage over tideless rivers, in which the current of the stream is always in one direction.'[2]

Regime of Rivers. 'Under natural conditions, the forces at work in a tidal river adjust themselves so as to establish an equilibrium between the eroding agency of the current and the tenacity of the soil of which the bed and banks are formed, and

[1] W. H. Wheeler: *Tidal Rivers*, pp. 114–5.

[2] W. H. Wheeler: *Ibid.*, p. 117.

the slope becomes so regulated that the velocity is sufficient for the transport of the detritus.

'When unconfined by banks, the direction also of the low-water channels through beds of sand and silt is the result of a balance of forces set up by gales, currents, floods, and other disturbing causes. A comparison of the charts of a sandy estuary extending over several years will show that, although at times the course of the channels may be altered by the prevalence of gales from one direction, of continued land-floods, or of long periods of dry weather, giving undue influence either to the tidal- or fresh-water agency, yet there is one course, of a more or less stable character, to which the low-water channel always reverts under normal conditions.'[1]

Junction of Rivers with the Sea. 'The angle of direction in which a river joins the sea is affected by the shape of the adjoining coast, the set of the tide, the direction and force of on-shore gales, and the travel of littoral drift.

'An examination of the charts of the coasts of this country will show that in the great majority of cases the line of direction of the main low-water stream where it enters the sea is nearly at right angles to the main set of the tidal stream along the coast, or inclining rather in the direction of the set of the tidal ebb and flow.'[2]

Source of Detritus in Rivers. 'Although there may be exceptions, the material which a river has to deal with is supplied from the interior, and not from the sea. Even where the tide flows over a vast mass of sands, such as those which lie along the coast outside the mouth of the River Mersey and the Ribble, or of the Humber and the Severn, it will be found that the tidal water flows into those estuaries bright and clear, and free from deposit, except in stormy weather, and that it only becomes turbid after it has mixed with the ebb.'[2]

Effect of obstructing the Free Flow of the Tide. 'Any cause that obstructs the flow of the tidal water and the free propagation of the tidal wave is detrimental to the maintenance of a river in its most effective condition, and leads to the shoaling of the channel.

'The placing of weirs across tidal rivers, contractions of the channel and irregularities in its form, restricted entrances, and

[1] W. H. Wheeler: *Tidal Rivers*, pp. 117–8.
[2] W. H. Wheeler: *Ibid.*, p. 118.

similar causes, are destructive to the maintenance of a deep-water channel.' [1]

Bars at the Mouth of Rivers.

Description. 'A bar across a tidal river (*cf.* Chapter I, Section I) may be described as consisting of one or more banks or ridges extending across the entrance channel, having deeper water both on the seaward and inner sides, and the crest rising above the general level of the bottom of the channel adjacent. In non-tidal rivers the bar consists of a long flat shoal at the mouth of the river, which rises so far above the general level of the bottom of the river, both at the outfall and in the channel above the shoals, as to render the channel useless for that class of navigation for which otherwise it would be fitted.

'Bars are not common to all rivers. At the mouths of most estuaries with sandy bottoms, ridges and depressions similar to bars are to be found, but in many cases, owing to the great depth of water over them, they cannot be deemed bars. In other estuaries where well-defined bars exist, the crests of these do not rise above the general level of the channel inside, and therefore do not form impediments to vessels going up or down the channel.' [2]

Bars composed of Hard Material not affected by the Scour of the Current. 'These bars consist of a shelf or ridge running across a river mouth, consisting either of stone, very hard clay, or occasionally of large boulders, or shingle cemented together with clay. Such bars can only be removed by dredging. The effect of the removal may be permanent, or the surrounding conditions may be such that the hard material may be replaced by sand, and the bar reappear.' [3]

Bars due to the Deposit of Alluvial Matter. 'These are to be found in tideless rivers, or where the rise and fall of the tide is so small as practically to render the river non-tidal.

'In *tidal* rivers, the ceaseless action of the tides, by which an enormous volume of water is poured into and discharged from the river twice every day, not only serves to keep the alluvial matter contained in water in suspension, but, by diffusing it throughout the whole volume of the tidal water brought in on the flood, carries the greater part of it away on the ebb and deposits it in the deep water of the ocean. In a *non-tidal* river the alluvial matter brought down the channel con-

[1] W. H. Wheeler: *Tidal Rivers*, p. 128.

[2] W. H. Wheeler: *Ibid.*, pp. 143–4.

[3] W. H. Wheeler: *Ibid.*, p. 145.

tinuously, and to a very much increased extent in floods, settles at the mouth of the river, where the current is checked and the velocity is reduced. In time, large deltas are thus formed, through which the water from the river finds its way to sea by several shallow channels.

'The large accumulations of sand found in most tidal estuaries vary considerably both in their composition and cause of deposit from alluvial deltas, and also in the fact that they are in situations where there is generally a considerable rise of tide. These sands are not continually accreting and forming deposits, but maintain their original form and extent in a more or less stable state so long as the natural conditions under which they exist remain unaltered. In the more open sea the accumulations of sand may be drifted along the coast during long-continued gales and form casual bars at the mouths of the rivers, but this material will be transported away when the normal conditions are resumed.' [1]

Bars at the Mouths of Sandy Estuaries. 'This form of bar is the type most frequently met with. They possess features of a most remarkable character, consisting of one or more ridges or mounds of material, the particles of which have not the slightest coherence, yet stand with a slope much steeper than their natural angle of repose. Rising in some cases as much as from 40 to 50 feet above the bottom, they maintain their positions across channels subject to a tidal rise of from 20 to 30 feet, through which currents run at a rate of from 3 to 4 knots, and the direction of which is reversed four times every day. Exposed to the storms and waves of the open sea, they are sometimes partly dispersed or added to, altering their position and shape, yet having a normal condition to which they are restored when the disturbing causes cease.' [2]

Formation of Sand-bars. 'A tidal bar assumes the form of a ridge, having deep water on either side. The ridge, being once formed, aids its own maintenance. Sand is moved in an estuary in a series of ripples or ridges, having a long slope on the upper side, or that from which the current is coming, and a steep face on the down-side. Over this steep face, or tip, the particles of sand are rolled. In a tidal channel where the current is continually being reversed, the position of this face varies with the direction of the tide. At the foot of the ridge a rotary or screwing motion is set up, which whirls the particles of material round the bottom of the hollow, continually tend-

[1] W. H. Wheeler: *Tidal Rivers*, pp. 146–7.

[2] W. H. Wheeler: *Ibid.*, p. 148.

ing to scour it deeper. The current moving forward along the bottom is deflected upwards, and rolls the particles up and over the ridge.'[1]

Channels where Bars are absent. 'Bars having been once formed and subsequently maintained by the action set up by their shape, if removed by dredging, are not liable to be re-formed, unless in situations where there is a strong littoral drift and the ebb current is not sufficient to keep this out of the channel. The conditions most favourable to the absence of bars are those where the estuary assumes a funnel-shaped form, decreasing in width and depth from the mouth upwards; when the momentum of the tide is not unduly checked; when there is a free propagation and long tidal run; when the ebb current is so directed as to have a preponderating force over the flood in the removal of material; and when the outfall channel is continued into deep water.'[2]

Theories as to Cause of Bars. Mr Wheeler, after discussing various theories in a paper laid before the Institution of Civil Engineers, sets forth the following views, which were almost unanimously accepted, and may be taken as mainly correct:—

'The existence of tidal bars is due to the action of the sea, and not to that of the land water. And the chief factors in their maintenance are tidal currents and on-shore gales.

'For their formation it is necessary that the bed of the estuary and of the adjacent sea should consist of sand or shingle, and that the depth of water should be sufficiently shallow to allow of the action of waves and tidal currents on the bed.

'Bars owe their origin and existence to the balance of forces which was established when the coast-line and estuary assumed their original form. These are forces which have continued to operate ever since, and which tend to build up or disperse them. The balance of forces originally set up, however, still continues.

'On coasts where there is a travel of material along the shore, it is drifted in its course across the opening in the coast-line which forms the outlet for the river. The flood-tide, setting through this opening into the estuary, tends to carry the material with it; the ebb-tide, on the other hand, tends to carry it back and disperse it into the deep water of the sea.

'Wherever there is any considerable motion of the water where the bottom of the sea is mobile, the material invariably lies in ridges, these in some cases being of considerable height. Bars

[1] W. H. Wheeler: *Tidal Rivers*, pp. 151–2.
[2] W. H. Wheeler: *Ibid.*, p. 152.

may therefore exist across the mouths of rivers where there is no drift along the shore, the sand being thrown up and assuming the form of a ridge or ridges, and thus forming a bar by the action of the wind, waves, and the tidal current, and being maintained by the action which its form sets up.' [1]

SECTION III. RIVER IMPROVEMENT SCHEMES

Works for the improvement of rivers may be undertaken with the following **objects** :—

(*a*) Prevention of or mitigation of effects of inundations.
(*b*) Increasing the facilities for navigation.
(*c*) Land reclamation.

The **methods** employed consist of:

(1) River regulation.
(2) Dredging.
(3) Canalisation.
(4) Construction of a lateral canal.
(5) Construction of storage reservoirs.

One or more of these methods may effect more than one of the above objects: e.g. *river regulation* may be primarily undertaken with a view to increase the facilities for navigation, and incidentally may prevent or mitigate inundations and also effect a certain amount of land reclamation. *Dredging* is usually a more or less temporary expedient to improve the facilities for navigation by deepening the channel or removing a bar at the mouth of the river, but it will probably have a considerable effect in mitigating inundations. *Canalisation*, by dividing the river into pools of water with a slight slope and abrupt vertical drops at the locks, is really a more elaborate method of river regulation. The construction of a *lateral canal* is likely to prevent or mitigate the effects of inundation as well as affording improved facilities for navigation. The construction of *storage reservoirs* is often undertaken with the double object of providing a supply of water for domestic and other purposes and preventing inundations—the storage reservoirs acting in a manner similar to lakes in the course of rivers (*cf.* Chapter VII, Section V).

River engineering is such an important branch of the engineer's profession requiring special study that it cannot be adequately

[1] W. H. Wheeler: *Tidal Rivers*, pp. 156–7.

treated here, and the reader is referred to Wheeler's *Tidal Rivers*, Vernon Harcourt's *Rivers and Canals* and article on 'River Engineering' in *Encyclopædia Britannica*, Van Ornum's *Regulation of Rivers*, etc., etc. A few of the more important geological considerations are, however, touched on below.

The Regulation of Rivers

Regulation may be effected by:

(*a*) Diminishing and controlling the flood waters.
(*b*) Straightening and controlling the river channel.

Flood Waters. The rise of a river in time of floods depends chiefly on the amount of rainfall and its distribution over the drainage area of the river, but it is largely affected by the nature of the strata in the river basin as well as by the nature of the river bed. As a general rule the hilly districts in which a river takes its rise are formed of impermeable strata with comparatively little vegetation; when the rainfall in these districts is heavy, the water flowing rapidly down the steep slopes of the upper branches causes floods in their lower portions where the slope is less, and carries with it a large amount of solid matter which is precipitated where the current is slower. Where the river bed is composed of hard rock very little erosion occurs, but where the bed is soft it is eroded by the strong current charged with solids during floods, while in normal times the current is insufficient to produce erosion and alluvium is deposited. All this alluvium tends to obstruct the current.

The main river is usually flattened, and in the lower reaches the current is easily deflected by corners formed of harder material or by any chance obstruction, and its course becomes more and more winding, the current impinging on the convex portions and corners being deflected against the concave sides of the bends and eroding them more and more. This is especially the case in the alluvial plains formed by former floods, where the course of the river sometimes becomes exceedingly sinuous.

Geological Survey. The first step to be taken by the engineer who attempts to diminish and control the flood waters is to make a careful geological survey of the drainage area.

There is often a close connection between the geology of the watershed and the amount of flow of the river.

In some rivers which drain a more or less impervious basin (*e.g.* clay) the dry weather flow is very small, or even nothing at

all, whereas during rainy periods there may be a very considerable flow. In such cases the flow also depends on the state of the weather; if evaporation is rapid as in the summer, the flow will be at a minimum, whereas in the winter when evaporation is very slow the river will be greater, thereby causing floods in the upper reaches.

In the case of a more or less pervious basin (*e.g.* chalk) some rivers have been found to discharge in the middle of summer as much as half the average annual rainfall, indicating that the river is fed by springs, resulting in a more uniform discharge throughout the year.

It is possible that in this connection the river may be supplied with water from outside its surface gathering ground; it may be fed from some other catchment which to the eye has no connection whatever with the river but is linked with it by the geological strata.

Geological Formation of River Bed. 'It may be remarked that when the bed of the river consists of silts, sands, gravels, and other drift material, there is, generally speaking, little difficulty in deepening by dredging. Not infrequently, however, these superficial matters overlie and mask dykes and ledges of rock which cross the channel, and then these require subaqueous blasting and more expensive methods of removal.

'A careful survey of the country will generally reveal where such obstructions are likely to occur, and the methods of removal may be suggested by a study of their structure above ground. In the case of the Wear, for instance, which in its lower course flows over the Magnesian limestone, harder dolomitic ledges may prove the obstruction to dredging; in the Tyne, it may be harder strata of Carboniferous sandstone; in the Tees, Triassic sandstones; and in the Clyde, it may be a dyke or dykes of columnar greenstone which reticulate the rocks in that area.' [1]

[1] David Page: *Economic Geology.*

BIBLIOGRAPHY

(In addition to works quoted)

ROYAL MINIKIN, R. C.: *Practical River and Canal Engineering.*

CHAPTER XIII

COAST EROSION

THE action of the sea, and the effects produced by it in denuding and reconstructing coast-lines, have been briefly referred to in Chapter I, Section I. Coast erosion is, however, a subject of so much importance to landowners and engineers, that the geologist and the engineer must again work together.

SECTION I. COAST-LINES

ORIGIN

In dealing with the subject of coast erosion we must first consider how the existing coast-lines originated.

Outline. Every coast has its own particular outline—its curves and indentations at some parts, its straight lines at other parts, are not accidental; for the forces which cause islands to be raised above sea-level also determine the main outlines of the coast.

Indentations and promontories, bays and water channels, may be due to old river-courses, to the action of rain, or to the nature of the rocks. Coast-lines have often been changed owing to crust movements.

Influence of Crust Movements (Diastrophism). Elevation and subsidence of land are referred to in Chapter I, Section II. The form of the coast sometimes indicates that *uplift* has taken place. Uplift, if widespread, will raise part of the continental shelf above the sea, with the result that the land is fringed by a coastal plain. In this case the outline of the coast will be regular and free from indentations, and on the shore-side of the coastal plain there will often be a sudden rise, or even a cliff, which marks the old position of the shore-line.

Again, the form of the coast may indicate that *subsidence* has taken place. Inlets, often with branches running inwards, show that the sea has entered the valleys. Each such inlet will be marked by a stream or river, and will be directly connected to the valleys. Such an indented outline is an indication that subsidence

has taken place, and is well seen on the Essex coast and in the west of Scotland.

Changes in coast-lines which are due to crust movements may be understood by studying the contours on a map of hilly country and imagining the sea to cover the land to such an extent as to leave nothing but a few islands, and then imagining the water to sink till the islands are all joined together so as to form large areas of land.

Uplift of land produces the same results—the coast-lines changing as the land rises.

Sea cliffs are formed by the wearing action of the tides (*cf.* ' Work of the Sea,' Chapter I, Section I). This action is accentuated when the rocks are inclined (*cf.* ' Dip,' Chapter II, Section II), as they are then more easily undermined and abraded. Inland cliffs and terraces at successive heights have been formed in this way.

Minor Irregularities. While the larger horizontal irregularities of the coast are chiefly due to crust movements, minor irregularities, such as bays and inlets, capes and headlands, reefs and islands, are chiefly due to the action of the waves dependent on the nature, structure, and arrangement of rocks on the coast-line.

The existence of these minor features is only intelligible by help of a knowledge of the ways in which the several geological formations which make up the dry land have been accumulated, folded, and upheaved, so that the edges of strata are exposed on the shores where land rises out of the sea.

These minor irregularities consist primarily of *projections* of the land into the sea, or of the sea into the land, some of which, such as inlets and headlands, are more or less generally normal to the general trend of the coast, while others, such as reefs and bars, are more or less parallel with it. The irregularities are generally either angular or curved in outline. Angular outlines are generally due to marine erosion alone, while curved outlines are usually caused by a combination of shore deposition or littoral drift with marine erosion.

Headlands. That the formation of headlands is due to geological causes is seen at Flamborough Head, Beachy Head, N. and S. Foreland, The Needles and Culver Cliff in the Isle of Wight. These headlands all consist of chalk which cannot be disintegrated by marine erosion, but can only be dissolved by the chemical action of water. It is, consequently, more enduring than the underlying and overlying sands and clays, and being a thick formation

and protected by a barrier of flints on the foreshore, it forms a headland on each side of which bays have been formed by tidal action, *e.g.* Sandown and Compton Bays.

Inlets. Where the strata have been bent into synclinal folds (*cf.* Chapter I, Section I) part of which is below sea-level, inlets have been formed, *e.g.* the Thames estuary and Southampton water.

Physiographical and Geological Considerations

Changes in Relative Level of Land and Sea. The coast-line of Great Britain affords ample proof that emergence and submergence of land have taken place in recent geological times, and it is generally agreed that these changes are due to crust movements (see above).

Raised beaches or *Strand-lines* are platforms, or terraces, formed in rock or gravel at sites which are often at successive heights above present sea-level. These mark the coast-lines of ancient shores. Behind them old sea cliffs are often found in exposed places, as well as caves worn by sea-water.

Raised beaches often may be identified by shells of marine organisms, and may be observed in the west of Scotland, in many European countries, and in Malaya, Australia, and Siberia.

Movements resulting in *submergence* are evinced by the drowning of the seaward ends of land valleys (*cf.* 'Influence of Crust Movements' above), and by the buried land surfaces along our coasts, where stone implements and bone needles, etc., have been exposed by excavations at or near Swansea and Southampton.

Submerged forests and beds of peat occur both on the east and west coasts of England, but there is little or no evidence that changes in the relative levels of land and sea are now in progress in Great Britain.

Evidences of *subsidence* of land are found in the south of Sweden, in Holland, Belgium, and on the west coast of Greenland.

The effect of the **nature, structure,** and **arrangement of rocks** on the coast-line, in the problem of coast erosion, is described in Section IV, but it may be remarked here that on the coasts of England and Wales there is a great variety of rocks which frequently change from one class of rock to another, *e.g.* granite and other igneous rocks, as well as the hard shales and slates of the Cambrian, Silurian, and Devonian; sands and sandstones of the Old Red Sandstone, Trias and Upper Greensand; thick clays of the Jurassic and London clay; various beds of the Cretaceous, and

notably the Chalk ; sands, gravels, loams, and clays of the Drift ; silts and peats of Alluvial beds ; sheets and strips of shingle, and wind-blown sands.

Many of these rocks are cliff-formers. In dip, conformability (*cf.* Chapter II), and relation to one another the beds vary to a large extent. Hence the study of our coast-line is not easy.

In the north and west of England and Wales, and in Scotland and Ireland, the older and harder formations predominate, as well as masses of igneous rocks. These rocks being more durable than those which lie to the south and east, the rivers which flow to the east have larger drainage areas than those which flow westwards.

SECTION II. FORCES ACTING ON COAST

The forces acting on the coast-line are:

(*a*) Sub-aerial agents.
(*b*) Cliff detritus.
(*c*) Action of the sea (see Section III).

Sub-aerial Agents

Sub-aerial Agents (see Chapter I) are air, rain, running water, frost and ice, plants and animals. To these may be added underground water. These agents are of great importance on many parts of the coast, especially where the rocks are soft and yielding (see Sections III and IV), causing the cliffs to disintegrate and producing large quantities of detritus. Sub-aerial agents act most strongly on the coast, because there is a free margin and the sea takes away the refuse.

Running Water. The streams and rivers, which conduct the natural drainage of the land to the sea, have a considerable influence on the problem of coast erosion. They carry large quantities of sediment out to sea, and thus may furnish material which is the chief implement used by the waves in their eroding action. They also form alluvial flats (see Section IV) and deltas (*cf.* Chapter I, Section I, 'Work of Running Water').

Underground Water. Land springs are referred to in Section IV.

Cliff Detritus

Littoral Deposits (*vide* 'Work of the Sea—Oceanic Deposits,' Chapter I, Section I) come under the head of Terrigenous Deposits, and consist of boulders, shingle or pebbles, gravels, sands, and other coarse or fine materials.

Sources of Beach Material. Almost all beach material is *derived from the land*, the greater part from erosion of the cliffs, a smaller part from abrasion of the foreshore, while a very small amount is brought down by rivers and streams.

The amount of material *derived from the sea bed* is practically negligible, but it is possible that a little may be due to scour of the sea bed in heavy gales, and some may be floated ashore by sea-weed attached to it.

By far the greater part of the detritus from cliffs is carried out below low-water mark, while some is deposited on the shore. Their relative proportions cannot be estimated at all easily. Some 90 per cent. of chalk is carried away at once, while rock, gravel, and clay cliffs yield from 20 to 30 per cent., but on the whole not more than 20 per cent. remains above low-water mark for long.

Some of this detritus is carried alongshore by the action of tides, waves, and winds, and is known as *littoral drift*. It has a powerful abrading effect on all submerged rocks, islands, and headlands, and becomes worn down into smaller pieces or grains. The lighter particles remain in suspension and are mostly carried out to sea, but some find their way back to the shore. The heavier particles are carried out to sea. The action of the moving sands and shingle is similar to that of the moving detritus in a river bed (*cf.* 'The Transporting Power of Water,' Chapter XII, Section I).

River Detritus. In addition to the material derived from the cliffs, a large amount of detritus is brought down by rivers and streams. Where it is discharged into the head of a bay or inlet, it is spread out on the shore until it forms alluvial flats and deltas, and may fill up considerable areas which are thus reclaimed from the sea (*cf.* Chapter XIV, Section II).

If a river or stream drops its load of detritus in the open sea, much of the detritus is moved by alongshore currents, as noted above, and either deposited in the sea or spread out on some distant beach.

Nature of Beach Accumulations. The nature of the materials accumulated on the shore depends chiefly on the nature of the rocks composing the cliffs, but also on the material brought there by littoral drift.

The sand usually consists chiefly of quartz grains, though fragments of other rocks and minerals may be present, and marine shells are not uncommon.

The deposits, though often distributed irregularly, generally

show a tendency to arrange themselves according to their degree of coarseness and their specific gravity.

Shingle and the heavier detritus are usually found between the high-water marks of spring and neap tides, but often extend beyond these limits. When the shingle, etc., are considerable in amount and free from sand, they often form ridges or 'fulls' sloping towards the sea, at the upper portion of the limits mentioned above. A mixture of sand with the shingle causes the latter to spread more evenly.

The pebbles vary in size and shape—flat ovoids are common. The larger pebbles are thrown highest up the beach. The material becomes finer and the slope easier towards the sea.

Sandy beaches sloping gently towards the sea occur where there are no cliffs, and in sheltered bays, while coarse shingle is found in bays, inlets, etc., on exposed shores, and muddy flats are brought to view, at low water, in estuaries and where streams debouch.

Littoral Drift is the travel of loose material close to the shore, caused by alongshore currents. It usually follows the direction of the tides, and is generally confined to the material lying between tide-marks, but may include some material below low-water mark.

Its movement alongshore is generally in a definite direction, which may be that of the flood tide, but is largely influenced by the direction of the wind. It is intensified in gales and may be increased by tidal action, and the contour of the coast has a very considerable effect.

Effect of Coast Contour. When the coast-line is straight, the direction of travel of beach material coincides with the direction of the flood tide, subject to considerations mentioned above, but when the coast is broken into bays and inlets, outlets of streams and rivers, or obstructed by artificial harbours, piers, or groynes, the movement of the drift is stopped by the headlands or other obstructions.

At the mouths of *estuaries* the movement of the drift is often complicated, depending on the strength of the tide and the force of the stream; sometimes it is carried out to sea by the strong current when the tide is flowing out with the stream, or it may drift up the margin of the estuary as in the River Wyre, where the shingle drifts as far as Fleetwood.

When the current is too weak to stop the movement of the drift, a bar may be formed.

The littoral drift may affect the *drainage of the land* by altering the position of the mouths of rivers or streams, or even closing them,

e.g. the mouth of the River Alde near Aldeburgh in Suffolk has been gradually deflected further and further to the south, and at Shoreham the mouth of the River Adur has been deflected to the east.

Effects of Tide and Wind. 'The relative effects of tide and wind on the condition of a foreshore are matters about which there exists much diversity of opinion, but there is little doubt that the prevailing drift is primarily and chiefly due to tidal action, although in heavy weather the direction of drift may be for a time entirely changed. During strong winds in a direction contrary to the trend of the tide, the normal travel of the drift may be nullified, and even reversed for a time. The accumulation of material on a foreshore is primarily due to tidal action in calm weather. A beach which has been seriously depleted during a long spell of heavy weather almost invariably makes up again, at any rate to a partial extent, on the occurrence of calm sea and cessation of wind. This replenishing is due to the return of a portion of the material previously drawn down into shallow water immediately below the low-water mark. That part which has been precipitated into the deep sea is, however, lost so far as the foreshore is concerned. Generally speaking, direct on-shore gales result in the drawing down of the beach material, and its gravitation towards the deep sea. Off-shore winds, on the other hand, frequently lead to the accumulation of material on a foreshore.' [1]

ORGANIC ACTION

Removal of Material from the Foreshore. The removal of shingle, etc., from the beach by landowners, builders, or local authorities, for building or road-making purposes, contributes to coast erosion in cases where the shingle, etc., has a normally protective effect.

Drainage. If land drains are allowed to discharge on the face of the cliff the rate of coast erosion is accelerated, particularly when the cliff is composed of incoherent materials, such as on the Holderness coast.

Need for Co-ordination in Coast Defence Works. It is important that defence works at one part of the coast should not have a bad effect on other parts; hence the need for a co-ordinating authority.

Rock-boring Organisms. Erosion below low-water mark is often aided by the action of rock-boring organisms, *e.g.* on the coast between Brighton and Newhaven, and at Selsey Bill. The most

[1] *The Engineer*, April 1906: 'Coast Erosion and Reclamation.'

destructive of these organisms are sponges, e.g. *Cliona*; molluscs, e.g. *Pholas*, the action of which is mechanical, and which make larger holes than any other organism; and *Saxicava*, which act chiefly on chalk and limestone rocks.

Plants. The effect of Marrum and other grasses, etc., on preserving sand-dunes (see also Section IV), and of marine algæ on encrusting rocks and forming submarine sheets of limestone, is referred to in Chapter I, Section I.

SECTION III. MARINE EROSION

The work of the sea is briefly described in Chapter I, Section V. Marine erosion is mainly due to the action of waves, tides, and currents combined, though wave-action is the dominant factor.

Waves

'Sea waves are of two kinds, forced and free; the former exist only during the continuance of the wind causing them, but the latter continue to run for some time after the wind has subsided.' [1]

Free Waves. 'Mr Hunt gives the following very concise definition of the character of oscillating, or free waves, as being that generally accepted:—

'"Such swells are composed of ridges above and depressions below the level of repose of the water.

'"They impart to a particle of water itself, or to a light floating object, a circular motion. Such particle describes the circle with uniform velocity, and in the direction of the motion of the wave itself.

'"The diameter of the circle is equal to the height of the wave from trough to crest.

'"From the circular motion of the particle it follows that, when above the level of repose, it is moving forwards; when below that level, moving backwards. In other words, the water composing the crest of the wave is moving forwards; the water composing the trough is moving backwards."

'The trough always precedes the crest in point of sequence. In this movement or oscillation it must be clearly kept in mind that there is no alteration in the position of a particle of water relative to the bottom after the wave has passed by; it is left in the same position in which the wave found it, having merely performed a circular oscillation in a vertical plane.

[1] Owens and Case: *Coast Erosion and Foreshore Protection*, p. 8.

'It is most difficult to rid the mind of the impression of an actual shoreward movement of the water itself when watching from a pier or cliff a series of these waves rolling in, and the remarkable way in which they retain their individuality. The motion of the water particles corresponds closely to that of a point in a long rope which is kept stretched out while one end is oscillated quickly up and down; a series of waves is seen to traverse the rope from end to end, but the rope itself is not drawn to either end.

'These waves are called "waves of oscillation" or "free waves," but there is another type of wave called a *wave of translation*, in which the water is actually permanently displaced by the wave; this type, however, will be dealt with later on.

'The oscillation of the particles of water, due to a wave of the first type, extends downwards through the water, the particles

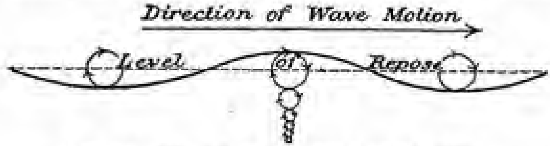

FIG. 43. Oscillation of particles of water.

revolving in smaller and smaller circles as the distance from the surface increases, until eventually the movement dies away (see fig. 43). It is, therefore, only a surface skin of the ocean which is disturbed by waves, but what the thickness of the layer is, is still open to dispute. It has, however, been proved that the oscillation in deep water decreases in amplitude in geometrical progression as the depth below the surface increases in arithmetical progression.' [1]

Waves of Translation. 'As free waves approach the shore they become more or less waves of translation, and the orbits of the water particles are not closed; the particles travel in orbits in a vertical plane, but do not quite return to the starting point. The velocity of the undulation or wave form is relatively rapid compared with the forward movement of water, which is slow and rhythmic, so the excess of forward movement over seaward decreases as we move seaward from the land margin and the depth increases. As the waves continue to roll into shallower water, their velocity and wave length are diminished and their height is increased; thus the waves are crowded together near the shore.' [2]

[1] Owens and Case: *Coast Erosion and Foreshore Protection*, pp. 9–10.
[2] Owens and Case: *Ibid.*, p. 13.

'**Forced Waves,** even in deep water, are not true oscillations; there is always a slight forward movement of the water as well as of the wave form, the former being relatively slow compared with the latter. Such translatory movement of the water tends to generate a surface drift with the wind. The relative amount of horizontal and vertical motion of the water due to a wave depends on the depth of the particle below the surface, and the total depth of water compared with the wave length. Where the water is deep, compared with the wave length, the horizontal and vertical movements are nearly equal, and their amplitude diminishes in geometrical progression as the depth increases in arithmetical progression.'[1]

'**Close to the breaker line** the nature of the motion of the particles is very different, the horizontal motion being nearly as great on the bottom as on the surface.

'Whenever there is any forward movement of water, caused by waves of translation, there must be a compensatory seaward current to remove the water brought shorewards by the waves. This probably exists in the form of an *under-tow*, the transporting power of which may be very powerful in shallow water, but decreases as the depth and distance from land increases.[2]

Breakers. 'When the wave rolling shoreward eventually plunges or breaks, its action becomes entirely changed.

'The action of such waves when breaking on a beach has been usefully divided into three separate parts or phases:

'(1) The "plunge," or act of breaking.

'(2) The "uprush" of water shoreward after the plunge.

'(3) The "backwash," or return seawards of this water.

'It is obvious that the plunge must violently stir up the bottom, and throw fine matter, such as sand, into suspension in the water; the "uprush" following immediately upon the plunge, therefore, starts highly charged with suspended matter, assuming sand to be present, or, if only shingle is present, a violent shoreward impact is transmitted to the pebbles. The current then carries this matter up the gradient shorewards; but on the water reaching its highest point, the velocity has died away, and there is a consequent *deposition of material*, which is left behind by the "backwash," since it has no such violent start to help it as the "uprush," but simply starts from rest. This action of the breaking wave is one of the

[1] Owens and Case: *Coast Erosion and Foreshore Protection*, pp. 13–14.

[2] Owens and Case: *Ibid.*, p. 14.

most complicated we have to consider. There is always a tendency for a balance to be attained between the relative transporting power of the "uprush" and "backwash." Obviously, considering the waves alone, and assuming them to strike parallel to the shore, the quantity of material carried by each determines the question as to whether erosion or accumulation is going on. The amount of matter carried up by the "uprush" tends to build up a gradient such that the help given to the "backwash" by gravity will counterbalance the help given to the "uprush" by the plunge.'[1]

Percolation, 'or the sinking away of the water through the interstices of the shore material, is a very important factor, and on shingle shores the force of the backwash may be much diminished. Gravity, however, is the controlling factor, and shores tend to assume an inclination of repose near H.W.M. such that the shoreward wash and backwash act with equal effect.'[2]

Overtaking of One Wave by Another. 'It will be noticed that this analysis of the action of the breaking wave assumes that the wave, when it breaks, has time to complete its cycle before it is interfered with by the following wave. This is not always the case, and if the waves strike the shore at such frequent intervals that the "backwash" of one is met by the "uprush" of the following wave, a very peculiar state of affairs is produced. At first sight one would say, here is a case where there must be a great accumulation going on, since the "backwash" is met in this way by the "uprush," and its scouring action presumably destroyed; but no, this is a most deceptive appearance, and is not borne out by closer observation, for instead of the checking of the "back-wash" by the water of the incoming wave, it simply glides up over the surface of the "backwash," thus completely reversing our first conclusion; for here we have an undercurrent flowing seaward, and on the top of it a landward current. It is thus obvious that the landward current cannot pick up any material from the bottom, and some of what it may already have in suspension will be robbed from it by the down-flowing undercurrent. This overtaking of one wave by another is very common, and results sometimes from a crowding of the waves on to each other by an on-shore wind. Of course, it depends also to a great extent upon the gradient of the shore, or any cause which is capable of increasing the frequency of the waves, so that the intervals

[1] Owens and Case: *Coast Erosion and Foreshore Protection*, pp. 14–15.

[2] Owens and Case: *Ibid.*, p. 15.

between them are less than the time taken for a wave to go through its complete cycle of "plunge," "uprush," and "backwash." The surf seen during on-shore gales is a further development of the same thing, all system being destroyed and the whole sea covered by a mass of broken foaming water.'[1]

Direction of Waves. 'In the above consideration it has been assumed that the waves strike the shore approximately at right angles to the shore-line, the waves themselves being parallel to the shore-line.

'Waves rolling in from the open sea tend to approach the shore parallel to the general coast-line, for the shoreward end of a wave, on entering shallow water, is more retarded than the seaward end in deeper water, and the line of the wave is thus swung round. The angle at which ocean waves strike the shore, therefore, depends partly on the gradient of the adjoining sea-bottom. The gradient has also an important influence upon the amount of material travelling: the flatter the gradient the less material will be moved per unit area, although in the aggregate more material may be moved on a flat shore than on a steep one, owing to the greater surface exposed to wave and current action.

'Waves generated near shore may run very obliquely to the coast-line; and we sometimes have two or more sets running at the same time in different directions. In shallow water the crests of these sets of waves may break where they cross, and exert a force which is the resultant of that which either would exert alone; for the depth of water in which waves break depends upon the height of their crests.'[2]

Oblique Waves. 'In whatever way produced, the action of oblique waves is very peculiar, and will best be understood by

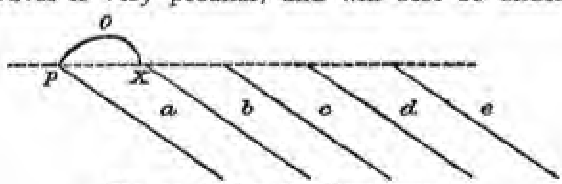

FIG. 44. Action of oblique waves.

reference to fig. 44, where *a*, *b*, *c*, *d*, *e* are supposed to be such waves, the dotted line representing the shore-line.

'When these waves break, the "uprush" does not travel straight

[1] Owens and Case: *Coast Erosion and Foreshore Protection*, pp. 15–16.

[2] Owens and Case: *Ibid.*, p. 16.

up the shore, but at an angle, nor does the "backwash" return straight down. The velocity of the "uprush" may be considered as the resultant of two components—one at right angles to, and one along, the shore. Now, when the wash of the wave travels up the beach, the velocity at right angles to the shore is destroyed gradually by gravity, but the other component is unaffected, except by friction, the result being that a particle of sand taken from any point P is carried up in a curved path to O, and down again to X, if not deposited, the final result being a movement of the particle alongshore from P to X. Hence these oblique waves cause a travel of material alongshore in the direction towards which they are inclined, or, in other words, in the direction of the wind, the individual path of each particle being approximately parabolic, such as is described by a projectile thrown at an angle into the air. The return path from O to X will, however, be somewhat steeper than the path from P to O, owing to the retarding effect of friction upon the horizontal component of the motion of the water particles.

'If the moving power of the "shoreward-wash" and "backwash" are not equal, the resulting movement due to oblique wave action may be either landward and alongshore, or seaward and alongshore. The more oblique the impact of breakers is on the coast-line, the more powerful is the alongshore drift.

'We thus see that the direction of wave impact is an important factor in the movement of material by wave action. This in its turn is governed by the aspect of the shore, its exposure, and the direction of the prevalent wind.

'The blows of large waves exert great disintegrating force on the shore material, and this is especially so when the forward motion of translatory waves is suddenly checked. There is no true wave stroke at levels lower than the troughs, and the most efficient impact of the waves is limited to levels between trough and crest.

'In considering the coastal movement of material, it is important to keep in view the fact that the power of waves to move particles on the bottom decreases rapidly as the depth of the water and the distance from the land increases.'[1]

Tidal Action

'This may be considered under two headings: (1) The effect of the slow rise and fall of the water-level, and consequent travel of

[1] Owens and Case: *Coast Erosion and Foreshore Protection*, pp. 16–18.

the water's edge up and down the foreshore; (2) the effect of currents and eddies set up, owing to differences of water-level and the reaction of the land upon the tidal wave.'

Slow Rise and Fall. 'We may dismiss the slow landward and seaward *current* as being too slight to have any effect in moving material unless the very finest suspended matter. There is another effect which is due to the travel up and down of the breaking point of the waves, and this is most important, as whatever action is going on at the time, due to the breaking waves, is applied successively to different parts of the foreshore, between H.W.M. and L.W.M., whether it be erosive or the reverse. If the tide rose and fell at a uniform rate, the result would be to plane out a uniform gradient between the breaking points of the waves at H. and L.W.; but this is not so, since the rate of rise or fall is very much faster at about half-tide level than at either H. or L.W.; hence the planing action is applied longer to the parts of the foreshore about these points than about mean sea-level, and whatever erosive or accumulative effect is being produced by the waves, is most marked just below H.W.M. and just above L.W.M. The bearing of this consideration upon the length of groynes is obvious, as it indicates that they should extend from above H.W.M. to below L.W.M.

'When parallel waves are eroding the shore, the above consideration shows that the result will be to cut out a section of foreshore something like that shown in fig. 45, hollows being

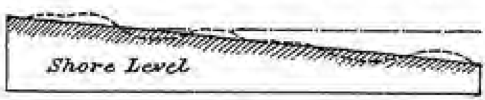

FIG. 45. Erosion by parallel waves.

dredged as seen, and corresponding hills or bars produced seaward of each hollow; whereas, if the waves were accumulating, this effect would be reversed, hills taking the place of the hollows, and *vice versa*.'[1]

Tidal Currents. 'The chief effect of tidal currents is probably to transport material already suspended or disturbed by wave action. Except where concentrated by narrow straits, etc., they are not usually sufficiently swift to move coarse material of themselves. These currents are, however, most efficient in carrying away matter suspended by wave action, or eddies due to a very

[1] Owens and Case: *Coast Erosion and Foreshore Protection*, p. 23.

rough bottom; and their preponderating effect, in determining the direction in which fine material eroded from the coast is transported, is shown very clearly by the great tendency for sandpits at the lee of headlands to point in the direction of the flood-tide and not in the direction of prevailing winds.' [1]

Joint Action of Waves and Currents

Movement of Material. 'The combined action of waves and currents may cause the movement of material on the sea-bed when either alone might not be able to do so. If, for example, the linear oscillation on the bottom, due to wave action, is taking place while

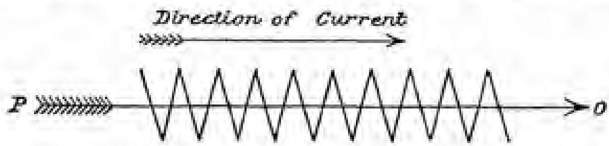

Fig. 46. Joint action of waves and currents.

a tidal current is flowing alongshore, this oscillation must become a zigzag, each oscillation being deflected by the current; so that the path of the particles on the bottom results in an alongshore movement, something like that due to the oblique wave action previously referred to, and as shown in fig. 46.' [1]

Wind-formed Currents

Effect of Wind. 'We have seen that in the case of forced waves, running in before the wind, there is a forward translatory movement of water as well as of the wave form. This slow, rhythmical advance of the water is an important element of the wind-formed current. The velocity of this translatory movement of water decreases from the surface downwards. When the wind commences to blow, the upper layers of water are drifted with the wind. This forward movement is gradually propagated to the lower layers, and, if the wind continues, eventually produces a movement of the whole body of water, if not too deep.

'The surface velocity of a current formed in this way is always less than the velocity of the wind causing it, and seldom exceeds one mile per hour. In shallow water near shore these currents are an effective means of transporting material.

[1] Owens and Case: *Coast Erosion and Foreshore Protection*, p. 25.

'When the surface drift moves against an obstacle, such as an island, or when its free onward passage is in any way partially obstructed, relief streams are set up, the velocity of which may be very great.'[1]

Undercurrents. 'An example of this effect is seen in the case of a wind blowing directly on-shore. This causes a surface current landwards, which is compensated for by a lateral or undercurrent seawards. It is an observed fact that on-shore winds denude a shore by removing material seawards; similarly, under certain circumstances, an off-shore wind may cause a surface current seawards, which is compensated for by an undercurrent landwards.

'Off-shore winds are never so effective in causing currents near the shore as on-shore winds, owing to the shelter of the land, since the strength of the current depends to a great extent on the fetch or distance which the wind blows across open water. The underdrift landwards will have little transporting power and will probably extend only a short distance from the land.'[2]

Alongshore Currents. 'It is seldom that a wind blows directly on- or off-shore, and, owing to irregularities of coast-line, it is always more or less oblique to some part of the coast. Any obliquity of direction causes the landward current to be partially deflected, and there is, consequently, an alongshore or littoral current. It will be observed that this current must assist the oblique waves in moving material in the direction towards which the waves are inclined. Such an alongshore current may be accompanied by an under-tow seawards.

'A wind blowing alongshore is most effective in causing an alongshore travel of the smaller particles of sand, shingle, etc. With such a wind we therefore get accumulation on the windward side and erosion on the lee of any obstacle which is capable of intercepting this drift. Hence the huge accumulation to the windward of high groynes, jetties, etc., and the almost invariable scour at the lee.'[3]

The sands, shingle, etc., thus accumulated often form dunes and ridges parallel with the beach.

When two converging coastal currents meet, the flow is reduced at the points of contact, with the result that the sands they carry settle, and sand banks and pits are formed.

[1] Owens and Case: *Coast Erosion and Foreshore Protection*, pp. 19–20.
[2] Owens and Case: *Ibid.*, p. 20.
[3] Owens and Case: *Ibid.*, pp. 20–22.

Scour

It is not the direct action of clean waves so much as the scour against the coast caused by waves and currents charged with sand, gravel, boulders, etc., which causes erosion, and has far more effect than much larger waves not so charged. The term *scour* is usually applied to the action of waves and currents charged with materials of this kind.

Clean water has little or no erosive action on hard rocks except when they have already been loosened along natural joints, etc., but where the rocks are soft or composed of unconsolidated material, the mere weight of water may disrupt them.

Just as in the case of rivers, it is by means of the sand, gravel, and stones which are driven against the sides and bottoms of their channels that erosion has taken place; so it is the sand, gravel, and pebbles, with which they are armed in heavy weather, that cause scour of the cliffs, etc.

Submarine Erosion and Deposition

Submarine Scour. The processes of erosion and littoral drift are not confined to the foreshore, but continue to affect the sea-bottom to whatever depth wave-action and tidal currents can be felt.

Wave-action affects the sea-bottom up to the edge of the continental platform—that edge which is marked approximately by the 100-fathom line. Beyond this line the sea-bottom shelves steeply into the oceanic abyss.

Any movement of material along the sea-floor is, doubtless, the result of the combined action of waves and currents. The tidal currents off our coasts have an average speed of from 1 to 3 knots per hour, and increase to 5 or 6 knots at times, *e.g.* round some headlands.

Sea-currents arise owing to differences of temperature and, at times, to prevailing winds. Currents at the bottom of the sea may run in an opposite direction to surface currents.

Submarine Deposition. As stated above, a large proportion of the detritus from the cliffs is carried out to sea, and while the effect on the sea-bed of these deposits, as distinct from local deposits, is inappreciable in recent times, it has a decided effect in the course of long periods of time. It has been estimated that the amount of detritus spread over the sea-level in 10,000 years would cause an elevation of 3 inches.

From time to time some of the detritus which has been carried out to sea is thrown back on to the foreshore, but seldom rests there, being returned again to the sea.

Islands and reefs, shoals, etc., lying parallel to the coast, afford protection from erosion by sheltering the coast from violent gales and strong sea-currents.

SECTION IV. EROSION AND ACCRETION

Coastal Erosion

Erosion is due to sub-aerial agents (wind, weather, plants, and animals, *vide* Section II), and to the action of the sea accelerated by detritus from the cliffs (*vide* Section III, 'Marine Erosion').

The rate of marine erosion depends on:

(*a*) The erosive and transporting power of the waves.
(*b*) The nature and situation of the coast-line.
(*c*) The resisting power of the rocks.
(*d*) Geological considerations.

The Erosive and Transporting Power of the Waves is dealt with in Section III.

When an on-shore wind accompanies a spring tide, the scour in a few hours may be greater than that caused by normal tides in many months.

The Nature and Situation of the Coast-line. A coast-line may consist of (*a*) cliffs; (*b*) a more or less level plain—perhaps not much above high-water mark; (*c*) marsh land.

Cliffs may consist of hard or soft rock, clay, sand, or gravel, or a mixture of any of these.

Level Plain. Such a coast-line is not liable to attack by the weather—only by the sea. Here the waves, aided by the wind, often heap up shingle or sand in the form of sand-dunes, and thus provide a defence against their own action.

Marsh land on a coast is usually below high-water mark, and protected from flooding by embankments or a beach higher than the marshes, which is known as a 'full.'

As regards *situation*, the rate of erosion on an exposed coast is much more rapid than in sheltered bays or on the lee of promontories.

Resisting Power of the Rocks. Hard and compact rock will resist erosion, but if permeated by joints, faults, or bedding planes it is far more easily attacked. The softer the rock, the more easily it is eroded.

Cliffs formed in well-compacted rock are usually steep or overhanging. Cliffs composed of incoherent material generally assume gentle slopes towards the sea.

If a hard rock is overlain by a softer one, the formation is known as *slope over wall*; if underlain by a softer rock, it is known as *wall over slope*.

In the former case the hard rock will resist the sea, and its resistance will be reinforced by the disintegration of the overlying soft rock, which will slip down and afford protection.

In the case of 'wall over slope,' the underlying soft rock soon disintegrates and brings down the hard rock, which then protects the soft rock from the action of the sea.

Compact *granite* often wears away into dome-shaped headlands and islands which resemble *roches moutonnées* (*vide* fig. 2).

When *stratified rocks* dip towards the sea, landslips are common, as, when undercut by scour, the supporting foot of the block is removed.

Landslips are often due to, or accelerated by, land springs.

Hence, when promenades, etc., are constructed at the foot of cliffs composed of rocks which dip towards the sea, or of incoherent materials, it is important to excavate very short lengths at a time and to fill in breast walls as quickly as possible.

Conversely, rocks dipping away from the sea are an obstacle to slipping.

Cliff Disintegration. Hard rock, where undermined, provides boulders and pebbles which become instruments of destruction. Soft rock usually disintegrates at once, but if there are any nodules of flint they are added to the shingle. When hard and soft bands of rock alternate, the soft bands quickly disintegrate and the hard rock, being unsupported, quickly crumbles away.

Chalk disintegrates rapidly under the influence of frost and rain, but is little affected by the sea, especially when massive.

Sand, loam, etc., offer little resistance to weather and waves. *Clay* suffers much more from the weather than from the sea.

Geological considerations govern to a large extent the amount and rate of erosion. The most serious erosion takes place in the south and east of England, on coasts lined with Tertiary and Secondary deposits, *e.g.* the London clay, gravels, and sands of the Glacial Drift on the Yorkshire and Essex coasts and the south shore of the Thames; the shelly crags, loams, and sands, etc., of Pliocene and later times on the coasts of Norfolk and Suffolk;

and Glacial and post-Glacial deposits on the shores of Scotland and Ireland.

On the south coast of England there is less erosion, and in the west of England and on the coasts of Scotland and Ireland the harder rocks of Palæozoic and Precambrian Ages resist attack. There is little erosion also on the east coast of England, north of Flamborough Head.

The nature of the strata below the low-water line is of great importance. If the strata resist submarine scour, a gently shelving foreshore will be formed, which will protect the cliffs from the action of the waves.

Springs and Landslips. The mode of occurrence of springs is referred to in Chapter VII, Section III, as largely dependent on the strata. Where pervious and impervious alternate is the most likely situation for springs.

Visible springs above high-water level cause landslips and tend to make a long backward slope, but they are not nearly so important as the lower springs, which occur between tide-marks or below the sea. These may cause the whole cliff to slip.

Coastal Accretion

Accretion above High-water Mark. Though a great deal of land has been lost by erosion, there has been much accretion on other parts of the coast. These take the form of accumulations of shingle, sand, and alluvium.

Shingle Accumulation. Storm beaches are masses of shingle accumulated above high-water mark in the course of storms.

Littoral drift often results in the formation of long spits which deflect the outlets of rivers and form ridges between the stream and the open sea, *e.g.* the ridge of shingle extending for 10 miles south of Aldeburgh (*cf.* above, Section II, ' Littoral Drift ').

Sand and Sand-dunes. These are referred to in Chapter I, Section I. Dunes are formed on coasts where much sand has been deposited by the action of on-shore winds, which drive the sand on to the land, especially where the land is low. They form a natural protection (*cf.* Section V).

The driving sand often interferes with the land drainage, and forms lagoons which get silted up into marsh lands, and eventually may be reclaimed (*cf.* Chapter XIV, Section II). On the other hand, the drifting sand often covers up valuable land.

To bind the sand and prevent it from drifting inland, as well as to encourage the formation of sand-dunes, where not existing, grasses are often planted with good results, *e.g.* Marrum (*Psamma arenaria*), lyme grass (*Elymus arenarius*), sand sedge (*Carex arenaria*), wild thyme, heather, gorse, sea-buckthorn, and tamarisk.

Alluvial Flats. The deposition of alluvium in sheltered bays and estuaries is referred to in Chapter I, Section I. Such alluvial flats can often be reclaimed (*cf.* Chapter XIV, Section II).

The process of raising salt marshes by the deposition of alluvial silt or mud is a very slow one, and the gains obtained are often not noticed in comparison with erosion, which is rapid and intermittent. The gains on the whole are probably greater than the losses, but as the land gained is always at a low level—below that of spring tides—the maintenance of protective works is often costly.

The process of natural accretion on alluvial flats may be expedited by planting Rice grass (*Spartina*) or other suitable vegetation.

SECTION V. PROTECTIVE MEASURES

Natural Protection

Beach Material. The shingle and sand which accumulates on the foreshore and are derived from the erosion of the land, form a natural protection to the coast. The protection afforded by sand-dunes is referred to in Section IV, ' Accretion.' Good examples are to be found in East Anglia, *e.g.* between Happisburgh and Winterton in Norfolk, and at Minsmere in Suffolk, where they form the only protection for wide areas.

The harm done by the *removal* of beach material has been referred to in Section II, ' Organic Action.' It not only contributes to coast erosion at the part where removal takes place, but also deprives adjacent places of material that would naturally accrue in the normal course. Moreover, cases have occurred where the hollow formed by removal has been filled by depleting the beach from some other point where its removal may have done much harm.

Artificial structures, *e.g.* piers and harbours, by arresting the flow of material, may also have a very harmful effect.

Again, the quarrying of rock on the foreshore, which protects the coast, may do injury.

The **preservation of sand-dunes,** by encouraging the growth of grasses, etc., is referred to in Section IV, ' Coastal Accretion.'

ARTIFICIAL PROTECTION

Imperfect Knowledge. One of the latest contributions to the study of coast erosion is a pamphlet by J. H. Van Der Burgt, Engineer of the Netherlands State Waterways Administration, translated into English and published in the *Royal Engineers Journal* for March 1937, and republished by the Institution of Civil Engineers.

He points out how little is known of the forces at work along those coasts, and the need for thorough exploration of all pertinent phenomena. He recommends the investigation of the reasons why protective works have or have not been found necessary on each part of the coast, and reiterates that comparatively little is known about it at present.

Need for Study. He also recommends study of the following :—

(*a*) The movement of sand along the coast;
(*b*) The motion of coastal currents;
(*c*) The under-water contours at various heights below low-water mark;
(*d*) The banks lying within estuaries;

and postulates the collection of data by means of hydrographic surveys, beach surveys, and soundings—especially where the coast is attacked heavily—and the recording of tide- and water-gauges.

The importance of **Co-ordination** in coast defence works and harbour works has been referred to in Section II, 'Organic Action,' and the need for a co-ordinating authority to prevent isolated attempts at protection and insist on the geological conditions being considered, is emphasised by the many wrongly designed works that have been erected.

Classification of Works. These include:

I. Measures for draining and shaping the cliffs.
II. Longitudinal works: (*a*) Sea-walls, (*b*) Sea-dykes, (*c*) Protected outer dunes.
III. Groynes.

The works under II and III may be used separately or together.

Drainage, etc., of the Cliffs. This includes the draining of water away from the tops of the cliffs, and is mentioned first because the neglect of such an obvious precaution—familiar to engineers making

mountain roads—may lead to the destruction of expensive works. This applies especially to the construction of breast walls on the cliff-side of promenades, etc., which if not done very carefully may lead to heavy falls (*cf.* Section IV, ' Resisting Power of Rocks ').

Longitudinal works include: (a) *Sea-walls* of masonry which are generally used to protect promenades at seaside resorts, or to carry railways and roads along the coast or elsewhere for some special reason, *e.g.* where the coast is very heavily attacked. (b) *Sea-dykes* or embankments to prevent inundation from the sea, as at Romney Marsh. These have a normal dyke cross-section. (c) *Protected outer dunes*, which may have a solid sea-wall, or the foot of the dune may be revetted.

Groynes are placed at right angles to the coast and spaced at regular intervals with the object of building up material so as to stabilise the low-water line.

SEA-WALLS

Effect of Wave-action. In considering the design of sea-walls it is necessary to bear in mind (1) the force of impact of a wave; (2) the height to which a breaking wave will rise.

The *Force of impact* of a wave will depend on (1) whether the wave is a tidal or a wind wave; (2) its length, height, and velocity; (3) whether the body against which the wave strikes is elastic or rigid, and whether it has a vertical or sloping face.

The power of the waves is mentioned in Chapter I, Section I. The most important point to note is the continuity of impact, ' like a continuous succession of cannon balls,' as described by Mr Thomas Stevenson.

The height to which a wave rises after impact. The height of a wave which breaks on a shore without meeting any obstruction will be no greater than the depth of water through which it is travelling, but where there is an obstruction, such as a sea-wall or cliff, waves may reach a height of more than 100 feet; *e.g.* at Wick, storm waves frequently overtop cliffs from 70 to 80 feet high.

Design. Sea-walls may have a vertical, sloping, curved, or stepped face. Their respective advantages and disadvantages may be summarised as follows :—

Increased scour at toe of wall is greater with vertical, sloping, and curved faces than with stepped face. In all the former an apron is necessary. Curved and sloping faces break the force of a wave by helping it to run up the wall, but the recoil is increased.

A wall with vertical face offers more direct opposition to a wave, and the dead blow on it is increased, but it reduces the tendency for a wave to rise and also lessens the recoil.

With a stepped face there is less scour. The ascending and recoiling waves are broken up, but there is a liability for displacement of the bricks forming the face of the wall.

The addition of a *cornice* to vertical and stepped face walls is a great advantage, as it throws back the wave and reduces scour.

Mass concrete is unsuitable for fronting sea-walls, but walls of mass concrete faced with blocks of stone or concrete have been used with success.

While every case must be considered on its merits, walls with almost vertical or slightly stepped faces are perhaps the best.

Dangers to which sea-walls are liable are as follows :—

(1) The toe is subject to attack by the backwash caused by the water running off the face of the wall and scooping out the sand. Stone aprons are used to combat this, but need careful watching, as the joints are liable to be scooped out by the backwash, forming hollows into which the stones sink.

(2) In heavy storms waves may sweep the top of the wall and carry away the backing, unless the latter is covered with asphalt, concrete, etc.

(3) Flanks of walls are liable to attack, and so should be thrown back by sloping the wall gradually back to high-water mark on the beach, and thus avoid corners.

(4) Pressure from behind the wall causing cracking or overturning may be prevented by filling behind the wall with broken stone or brick instead of earth.

Groynes

Groynes with or without a sea-wall have the effect of stopping the travel of shingle along the shore, and of raising the beach-level by accumulating shingle. They are often needed in front of sea-walls, and in that case should be constructed first to prevent scour along the foot of the wall when built.

The higher the groyne the greater will be the accumulation on the windward side. Groynes should be built far enough out to sea to prevent shingle escaping round the end, and erosion taking place below low-water line.

Groynes are best adapted for a sloping beach. They are not suitable where there is deep water close inshore.

It is not possible to go into details of groyne construction here, but it is important to remember that a groyne is useless without a secure foundation. Sheet piling is much used for this purpose.

Fascine mattress work covered with random rock rubble is much used on Belgian and German coasts, in front of and alongside the groynes, and where the sea attack is heavy, very heavy stones are placed over the mattress. The mattress work is gradually narrowed up the beach, and should be carried up to half-tide level.

The leeward groyne of a series is likely to produce serious scour on its leeside, and may be protected by *spur groynes*.

BIBLIOGRAPHY

(In addition to works quoted)

LATHAM, ERNEST: *The Maintenance of Foreshores.*

LATHAM, FRANK: *The Construction of Roads, Paths, and Sea Defences.*

Third Report of the Royal Commission on Coast Erosion, etc.

MATTHEWS, E. R.: *Coast Erosion and Protection,* revised by Brysson Cunningham.

VAN DER BURGT, J. H.: *Coast Protection on the North Sea Coasts of Holland, France, Belgium, and Germany; R.E. Journal,* 1937.

WILLIAMS, Engineer Lieut.-Commander W. A.: *Inland Waters and their Sea Approaches.*

CHAPTER XIV

DRAINAGE AND RECLAMATION OF LANDS

Processes affecting Land Surfaces. Whereas the principal agents producing swamps and flooded areas on such a large scale as to call for reclamation are seas and rivers, the processes of denudation, deposition, and evaporation are common to lands requiring reclamation as well as to smaller areas, such as farms and estates, which come under the head of Drainage of Lands.

Denudation and Deposition. The agencies described in Chapter I, Section I—changes of temperature; solvent and chemical action air and water; disintegrating action of frost, ice, and snow; action of rain and running water above and below ground; action of plants and animals—all tend to break up the surface of the land and reduce large masses to smaller ones, especially on the steeper slopes and more exposed surfaces.

The detritus so formed is carried down by streams and rivers, glaciers and earth movements, from higher levels and deposited on lower levels, where the process of comminution is continued more slowly towards or into the open sea, where it is subjected to the action of waves and currents.

Rainfall is referred to in Chapter VII, Section I, and the physiographic conditions affecting the flow of streams and rivers is referred to in Chapter XII, Section I, while the action of waves and currents is described in Chapter XIII.

Near the seacoast swamps are formed when the nature of the land is such as to permit denudation to lower the land surface until it becomes flooded by the sea, and reclamation is carried out by processes which induce the sea to return sediment to the land.

Similarly in areas inland, where the natural drainage, shaped by the rainfall into rivulets, streams, and rivers, is either in excess or deficiency of agricultural and other requirements, a system of artificial drainage is required in order to carry off surplus water or to check the run-off and distribute it among fields, etc.

Evaporation is referred to in Chapter VII, Section I, and must be taken into account in all reclamation and drainage schemes.

We are not concerned here with evaporation from the surfaces of water, but only with that from ground surfaces, which, as stated in the passage in this book referred to, will depend on (i) the temperature ; (ii) the physical configuration, and the geological formation; (iii) the nature of the surface, and the amount of vegetation ; (iv) the rate at which rain falls, and the height of the water-table.

The humidity of the atmosphere depends on the amount of rain and the temperature. On steep, bare, and impermeable surfaces the amount of evaporation will be least, and on flat permeable surfaces it will be greater—and, if the water-table is near the surface, the amount will be greater still. On the other hand, absorption by vegetation must be taken into account.

Evaporation is least active when the humidity of the atmosphere is greatest.

Generally speaking, the amount of evaporation varies so much that, in drainage schemes, it must often be ignored.

SECTION I. DRAINAGE OF LANDS

Drainage. Owing to the above-mentioned processes of denudation, deposition, and imperfect evaporation, an excess of water is apt to accumulate in low-lying lands. *Drainage* is the process of removing this surplus water from the soil and subsoil by natural and artificial means.

All **water in the soil** is derived originally from precipitation, but in any particular area the amount actually precipitated may be increased by surface flow or underground seepage from higher ground or by springs. An excess of water is injurious to crops, for they need an access of air to their roots, and when the ground is saturated with water the air is all driven out, and, owing to the continuous process of evaporation and radiation, the temperature of the water-logged soil is much below that of drained soil.

Water will rise in clay by capillary action to a height of 50 inches, and in sand to 22 inches. Above the water-table the water is held by capillarity, and the percentage of water so held decreases towards the surface, which may be perfectly dry.

Drainage reduces the 'surface tension' of the capillary water by removal of the excess, but the water-table may be much below.

Drains should be capable of removing the excess capillary water, as well as the excess of percolating water in wet weather.

The measure of 'run-off' employed by drainage engineers is

called the *drainage coefficient*, and is the depth of water in inches which must be removed from the entire watershed to be drained.

Methods of Drainage. Drainage may be effected by (1) surface drainage, or (2) underground drainage by means of pipes, etc. The result is to increase the flow of water in the streams and rivers to which the system of drains is connected (see Chapter XII, 'Rivers').

In designing a **system of drainage** for an estate, etc., the first step is to arrange for a suitable *outfall* into a river or other receiving channel; the main drains must then be arranged for—these should be laid along the bottoms of the principal valleys. Branch drains may be needed in the smaller valleys and hollows, and these will be fed by minor drains or feeders, which are usually parallel to one another.

Size, etc., of Drains

The **size and general arrangements of the drains,** whether surface or underground, depends on:

(*a*) The amount of the rainfall.
(*b*) The contour of the ground.
(*c*) The geological strata of the district.
(*d*) The nature of the soil.

Amount of Rainfall. Rainfall is referred to in Chapter VII, Section I. The maximum quantity of rain per diem must be allowed for. The width between drains should be in reverse proportion to the amount of the rainfall. A fall of 1 in 200 is desirable.

Contour of the Surface. The amount of water to be dealt with—which is the drainage engineer's problem—obviously depends on the general contour of the ground. In hilly districts rain-water collects into runlets and streams, which not only have a marked erosive effect, but often remove too much water from the soil; so that it may be necessary to lead water to the land by banking up the streams instead of draining it away.

Lower down, the streams collect into rivers, thus forming a natural drainage system. The erosive effect depends largely on the valley-slopes. The wider the valley, the slower the velocity of the river.

When the rivers reach lower ground, deposition takes the place of erosion, which may raise the river bed and cause the river to overflow—thus necessitating special drainage measures.

In valleys with considerable slope catchwater drains may be needed; while those with less slope, in average undulating country, can be drained by a regular system of surface drains.

Land below the level of the sea may need draining by boring absorbent wells down to a permeable stratum, if such is available.

Geological Strata. The geological formation is of paramount importance in all drainage schemes, and the engineer will do well to make a careful geological survey (*vide* Chapter VI).

The strata may be classified for this purpose as follows, viz. (1) porous or pervious, *e.g.* sand, gravel, etc.; (2) retentive or impervious, *e.g.* clays, marls, dense rocks, etc.; (3) mixed or partly pervious, *e.g.* loam, soft chalk, and surface soils of mixed ingredients.

Where there is a pervious bed resting on an impervious one, it will usually suffice to take the main drain down to the bottom of the pervious bed, but where there is an impervious bed resting on a pervious one, if the latter is not very deep it will be best to take the drain down through both beds.

Again, if the surface is concave, as in valleys, basins, etc., larger drains will be needed, and catchwater drains will be required also.

A thick bed of clay can only be dealt with by laying shallow drains fairly close together.

The depth of drains and their distance apart depend largely on the texture of the soil. In an impervious soil the flow is much impeded, and the water-table can be controlled only by a large number of pipes. In lighter soils the depth and distance apart can be reduced.

Nature of the Soil. Soils and subsoils are referred to in Chapter XV, Section I. We are here concerned with soils in relation to drainage. These may be considered under the following heads: (1) Free soils, (2) Clay soils, (3) Peaty and vegetable soils, (4) Mixed soils.

Free soils, e.g. sands or gravels, neither oppose the admission nor effect the retention of water. If deep enough to reach the 'water-table' (*cf.* Chapter VII, Section II), the water of imbibition, as it rises by capillary action, will be partly evaporated, partly absorbed by vegetation, and partly drained off by natural means to lower levels, if such exist.

Clay soils absorb water slowly, but allow little, if any, to percolate through them. When wet, they expand and retain moisture, but when dry they contract; they part with their water by evaporation, and by drainage through the various cracks and fissures which

occur as the clay dries. They require the most complete aeration to enable them to be drained efficiently. This aeration is obtained through the cracks and fissures, and by means of artificial drainage.

Peaty soils are capable of a large amount of capillary action, and consequently lose much of their water by evaporation. When drained, they react more quickly than clay soils.

Mixed soils consist of a mixture of aluminous, siliceous, and calcareous materials in varying proportions. They retain water and lose it by evaporation in proportion to the amount of alumina present. They are generally found in the form of clods, between whose particles are pores which will contain water, while the passages or canals between the clods should contain air, in order to form a soil suitable for agricultural purposes. When the passages between the clods are filled with water the soil is said to be water-logged and unfit for tillage.

SECTION II. RECLAMATION OF LANDS

The subject of reclamation of lands from the sea is closely allied with that of the drainage of low lands.

The actual work of reclamation is carried out by controlling the deposit of alluvial matter which has accumulated, as described in Chapter XIII, Section II, 'Sources of Beach Material,' and Section IV, 'Coastal Accretion.'

Causes of Failure in reclamation work are:

(*a*) Want of co-operation among landowners, etc.

(*b*) Want of recognition of the fact that land reclaimed from marshes, or by warping (see below), will shrink on drying when drained. This may involve pumping.

(*c*) Unsuitable embankments, *e.g.* either too low, or badly built, or not properly protected or maintained.

(*d*) Unsuitable sluices, *e.g.* too small, or badly constructed so that they leak.

(*e*) Unsuitable drains, *e.g.* either too small, or allowed to silt up and get choked with vegetation.

RECLAMATION OF TIDAL LANDS

The chief object of reclaiming land from the sea or in tidal areas is to enlarge the area of ground which is available for cultivation. The fresh alluvial soil deposited in reclaimed areas is usually very fertile.

Land may also be reclaimed for harbour purposes, as for the new Southampton docks.

Along most of our fens, levels, carses, and tidal estuaries there is always a considerable margin of silt and low-lying land, little if at all above ordinary sea-level, and consequently liable to be inundated during flood-tides and storms.

Natural Reclamation. The formation of alluvium is referred to in Chapter I, Section I. As stated in Chapter XIII, the larger proportion of material brought down by rivers to the sea, as well as of that eroded from the coast-line, is carried out to sea, but much of the finer material is deposited in estuaries and sheltered bays, and becomes the groundwork from which alluvial flats are formed, which by slow degrees may be reclaimed and converted into good agricultural land.

The first step in the reclamation of alluvial flats is the formation of salt marsh by *natural accretion*, either outside the banks of areas already reclaimed as in the Wash, or off the shore as in Southampton Water.

Where there is a substratum of clay, as in the cases cited, sand is deposited by the tides, and above this sand alluvial matter or 'warp' follows. First, the larger particles of silt and sand are deposited, the finer particles being carried away by the ebb, but as the foreshore rises and the strength of the ebb grows less, the finer particles of warp begin to settle. When the warp begins to accumulate, *samphire*, followed by marine grasses, begin to grow. These assist the warp in accreting.

The various stages in the growth of vegetation in the reclamation of alluvial flats are as follows:—

First come algæ and bacteria, then marsh samphire or glasswort (*Salicornia*). The samphires induce the formation of hummocks of mud, which gradually become colonised by sea-blite and sea-grass. The hummocks gradually grow and coalesce, and the depressions between them become filled up.

The plants of a salt marsh differ from others in their capacity to endure periodic immersion in sea-water.

The growth of rice-grasses on the mud at Southampton did much to accelerate the natural accretion, thus facilitating the work of the engineers in the eventual reclamation.

In the Report of the Royal Commission on 'Erosion, etc.,' it was stated that a period of at least twenty to thirty years is necessary before the grass becomes fit for enclosure, and that if the land

has been enclosed too soon it has been found worthless for cultivation, owing to the lack of sufficient organic matter derived from the long-continued decay of marine vegetation.

Artificial Reclamation. When the natural accretion has considerably progressed, artificial aids must be resorted to in order to complete the reclamation. These consist of *embanking*, *warping*, and *draining*.

An *intermediate stage* between natural and artificial reclamation is often resorted to, by placing fascines, hurdles, or sods across the line of flow in order to reduce the scour. Embankments are then commenced so as to enclose the higher portions of the foreshore, and ultimately extended so as to enclose the whole area.

The *embankments* of the old reclamation of Romney Marsh, and many of the Dutch embankments, were made without any puddled wall—the width of the bank sufficing to prevent percolation of water at the base; but where there is any likelihood of infiltration, a core of puddled clay is required as in the reclamation bank for the Hod-barrow Iron Mines, or a row of sheet piling may be used.

The height of the bank must be sufficient to prevent it being overtopped by waves, and allowance should be made for a spring-tide accompanied by a strong on-shore gale. To prevent the bank being undermined by the action of the waves, a line of sheet piling may be placed along the outer toe of the embankment.

As a rule, embankments in estuaries should not be built beyond half-tide level, and it is preferable to reclaim a large area at one operation rather than by sections. The best method of finally closing the bank is to leave a fairly wide opening and gradually raise a level bank the whole length of the opening. In Holland, the openings are closed by sinking long mattresses of fascines which are weighted with stones and clay.

Warping is the process of admitting muddy water from the estuary or tidal river into the area which it is intended to reclaim, which must be below the level of high tide, and letting this water slip again as the tide falls.

Strong sluices for this purpose are provided in the river bank or bank of the estuary, and channels are constructed to carry the water to the area to be warped, which is enclosed by an embankment in which sluices are made to control the flow. These sluices are placed as low as possible so as to admit water at the lowest part

of the tide, just before it begins to turn, at which time it is charged with more mud and silt than at any other time. The main channels or conduits often extend for miles, and, being very costly, serve for several areas, fresh openings being made in the embankments as required.

The 'warp' or fine muddy sediment thus deposited is derived from the banks and bed of the river, part being brought down by tributary streams above tidal limits, and part scoured out by the action of the tide.

The result of warping is to enrich the soil. A deposit of 2 or 3 feet may be attained in one season, and thus the land is gradually reclaimed and made fertile.

Drainage. The land must be prepared for warping by constructing channels to lead and distribute the water where required. These are kept open by the outflowing water when the tide recedes. These channels are utilised as drains to effect the drying of the land when the warping process is completed.

It must be remembered that the drying-up process lowers the surface of reclaimed land some 2 or 3 feet, and it is therefore important to make the embankments strong enough to prevent any chance of breaching.

Reclamation of River Lands

River improvement schemes (*vide* Section III, Chapter XII), which are generally undertaken with the object of deepening the river channel for the purposes of navigation, may also effect the reclamation of considerable areas of land.

Embankments or **Levees** (as they are called in America) may be natural or artificial.

Natural Banks. We have seen in Chapter I, Section I, that deposition of sediment takes place when the velocity of a stream is checked and that alluvial fans are thus formed; also in Chapter XII, Section I, that terraces are often formed on the banks of rivers on account of the velocity of the stream near the banks being insufficient to move heavy materials. In a similar way deposition takes place at the sides of the stream where the velocity is less, with the result that the banks are raised and the whole bed of the river is gradually uplifted above the level of the surrounding country.

In time of flood the stream overflows its banks and deposits more material on the outer slopes, so that a long alluvial ridge

or natural levee is built up on each side of the stream. A notable instance of this action is the Hwang Ho or Yellow River in China.

Artificial Embankments. When it is desired to protect low-lying land adjacent to the bank of a river, the overflow of the river must be confined between continuous embankments. A low-lying district thus protected, as a rule, will be a long, narrow strip; its width being the space between the embankment and the nearest high ground, whilst its length may be from one tributary of the river to the next. Usually, it will be necessary to carry the embankment back to the high ground at each end of the district to be protected.

A low embankment may suffice where it is necessary to exclude only exceptional summer floods; or the embankment may be high enough to exclude all but exceptionally high floods—provision being made for the escape of the exceptionally high floods at certain places where the discharge is least injurious; or, again, the embankment may be high enough to exclude the very highest floods.

In any case, allowance must be made for the drainage of the protected district, and provision for the discharge of water from adjacent high land may have to be included.

Where the embankment is high enough to guard against the very highest floods, it must be exceptionally strong and perfectly watertight; allowance must, of course, be made for the rise in height of the water in the river due to confinement within embankments. Provision must also be made to prevent seepage water percolating under the embankment.

In certain cases pumping may have to be resorted to, in order to remove the water from the district to be protected. The great expense of this process precludes its use, except in the case of lands the return from which will warrant it.

Location of the Embankment. The exact location, or distance from the river, of the embankment depends on local conditions, the most important point being to secure a solid foundation. The volume of flood-water to be dealt with; the nature of the soil of which the banks are composed; the general stability and slope of the ground to be enclosed; as well as the slope of the ground adjacent to the site of the proposed embankment, must all be taken into consideration.

As a rule, the embankment will be parallel to the river, but the

general direction may be varied to take advantage of high ground, care being taken that any changes in direction are formed by means of easy curves.

BIBLIOGRAPHY

DEMPSEY, C. D., and CLARK, D. K.: *Drainage of Lands, etc.* (Crosby Lockwood).

ELLIOTT, C. G.: *Engineering for Land Drainage* (Chapman and Hall).

CHAPTER XV

SOILS AND SITES FOR BUILDINGS

SECTION I. SOILS AND SUBSOILS

THE nature of the several soils with which we have to deal will best be understood by regarding the manner in which they have been formed, and the several materials of which they are constituted.

FORMATION OF SOILS

The formation of all soils may be very clearly traced to the disintegration, by mechanical and chemical agencies, of rocks and minerals which contain alkalies and alkaline earths.

The origin of soils from the disruption of rocks is referred to in Chapter I, Section I, and the disintegration of rocks is described in Chapter V, Section IV.

Classes of Soils. Soils may be (1) formed *in situ*; (2) formed by the mechanical effects of rain and running water, *e.g.* alluvial soils; (3) Upland soils; (4) Glacial soils.

Soils formed in situ. In all surfaces flatter than the angle of rest, the products of weathering and disintegration will tend to accumulate where they were formed.

As the crust weathers and begins to break up, mosses and lichens establish themselves, and push their tiny rods down into the crevices in the rock-surface. From the decaying vegetation humic and other organic acids are produced, and continue the work of disintegration. The rock-surface gradually becomes comminuted into the finest particles which, becoming mixed with the decaying vegetable matter, forms a thin layer of dark-coloured humus or soil (*vide* fig. 1).

This thin layer soon attracts other plants and grasses, shrubs and trees, whose roots strike down deeper into the crust, break up the surface still more and increase the supply of organic and other acids (see 'Forest Action' below).

The work of disintegration is still further carried on by earthworms and micro-organisms, by whose means the whole soil layer is largely reconstituted.

As the process continues, and the depth of soil gets beyond the limit affected by roots of plants, shrubs, and small trees, a more compact layer gradually intervenes between the soil and the rock (see 'Subsoil' below).

Alluvial soils. The action of mountain torrents, in bringing down silt to form alluvial terraces and plains, has been described in Chapter XII, Section I. At first these alluvial plains are swampy, but gradually many of them become good firm soils, either by continued deposition or continental uplift. Where neither of these operations of Nature takes place, it is often possible to drain them by artificial means (see Chapter XIV, Section II, 'Reclamation of Lands'), as in the case of the delta of the Rhine.

The peculiar advantages of this class of alluvial soils are their depth, which is often very great, and their extreme fertility. Moreover, owing to the absence of stones they are easily ploughed, and their products can be disposed of by means of the adjacent waterways.

Upland soils. These are beyond the reach of the silt-laden flood-waters, and as a rule their slope is too small for gravitation to come into play and induce detrital matter to creep down the slope into the lands affected by the flood-waters.

On such lands the wasting of the soil is mainly occasioned by the direct cutting action of rills and streams, or by the percolation of water through the mass of earth and rocks. A portion of the material is dissolved by these percolating waters, which carry it away to the streams in a state of solution.

Glacial soils. The deposits due to the Glacial Period are fluvio-glacial drifts, moraines and valley trains, boulder-clays, newer glacial drifts and eskers (see Chapter I, Section I). When the ice melts, the stones, pebbles, sand, and mud from these deposits, which have been carried along with the ice, drop on the surface and form a coating of detritus, often very different in character from that of the underlying surface. Owing to the nature of its formation, this detritus breaks up into soil far more quickly than in the case of unbroken rock, but owing to the presence of large stones, and to the fact that they are washed over by streams of water from the melting ice and thus deprived of the clay which is the finest element of a soil, they are only relatively fertile.

Fertility. The fertility of soil depends on the chemical character of the rocks from which they are derived. If the composition of the rocks has a wide range, the soil is likely to be fertile unless it is too

fine-grained to retain the moisture which is so necessary for plant life.

The fertility of soils is also due to the presence of organic remains in the underlying rocks. These are most common in stratified rocks, but are also found in crystalline rocks. The lime phosphates, so essential in soils used for agricultural purposes, are derived from small shells and minute crustaceans.

Effect of Air. The aeration of the soil is produced in various ways. Roots of trees, when they decay, form cavities, and larger cavities are formed by the blowing down of trees. The action of burrowing animals has been referred to in Chapter I, Section I. Water steadily penetrates downwards into the soil and takes with it a certain amount of air. Moreover, as it sinks into crevices and cracks, it draws down still more air.

Forest Action

Effect of Clearance. The effect of clearing forests whereby the run-off of water into streams and rivers is greatly accelerated, is described in Chapter XII, Section I. The effect of forests on soils must now be considered.

The **dense mat or sponge of vegetation** found in forests protects the soil, and so retards the downward movement of this material towards the sea which is always taking place, that before it reaches the banks of the streams most of the plant food is taken from the waste and fed to vegetation.

When, however, this natural coat of vegetation has been cleared away, and still more when the land has been subjected to the plough, the rate of removal of silt from the surface of the soil into streams and rivers is greatly increased. If the slope of the ground be steep, this action will be still further accelerated, and a single torrential downpour of rain will carry away an enormous amount of soil.

The dense mat of vegetation, already alluded to, not only stores up water in a natural reservoir and yields it, but slowly, to streams and rivers, equalising their flow and maintaining a steady supply of water for the purposes of mankind, but also protects the soil from erosion and increases the rainfall. For, in the case of a cleared surface, water runs off rapidly and there is little opportunity for evaporation. But from a damp surface, evaporation, condensation, rainfall, and re-evaporation form a continuous process.

The **destructive action of trees** in breaking up the soil has been described in Chapter I, Section I. This action is of course

intensified in the case of forests. The chemical action of rain as regards oxidation, deoxidation, carbonation, etc., as described in Chapter I, Section I, is greatly increased by the acids dissolved from the vegetation beneath the branches of forest trees.

Subsoil

The subsoil is really the weathered portion of the underlying rock and merges almost imperceptibly into the soil. It differs from soil in being more compact and in containing particles of rock from the underlying stratum. It usually takes its colour from the latter, but may be yellow or brown owing to the oxidation and hydration of iron.

SECTION II. BUILDING SITES

In choosing the site for a building, whether for residence or other purposes, one of the most important considerations is the nature of the ground on which it is to be built. No less important is the actual position of the building as regards light, air, and relative elevation, and its construction, water-supply, and drainage; but these latter are matters beyond the province of the geologist, whereas he can throw light on the question of the foundation.

It is usual to refer to 'the subsoil' in this connection, but, as will be seen, buildings may be erected on made ground or on rock, where there is no subsoil properly speaking.

Foundation. This term is used (1) for the supporting part of a wall or structure, *e.g.* piers or column, and includes the base course and footing course—we will call this the *Structural Foundation*; (2) for the ground material on which something is built—we will call this the *Ultimate Foundation.*

Structural Foundation

Footings are provided to distribute the pressure of the walls of a building, and, together with the *concrete* bed—which is usually provided—to reduce the pressure to a safe margin below that which the ultimate foundation will stand (see below).

In the case of piers and columns, where the load is more concentrated, the proportions of the structural foundation must be correspondingly increased. In the case of hard rock, theoretically footings may be unnecessary; but see under 'Ultimate Foundation' below.

Ultimate Foundation

Natural Soil has been described in Section I of this chapter (see Soils formed *in situ* '). It is of varied composition, dependent on the nature of the rocks from which it is derived, and is, at times, further modified by the action of wind-borne material (see Chapter I, Section I).

As a rule, the natural soil is not more than 3 feet thick, and though thicker on the lower slopes of hills and in valleys, it does not generally affect the sanitary conditions of a building site.

Made Ground. Much of the surface soil of our cities and towns is a mixture of mould, sand, loam, or clay, with debris from old buildings, and rubbish. Generally it has been turned over and over till brickbats, broken crockery, and all sorts of odds and ends are mixed up with the soil and subsoil. It may be of considerable depth, especially where old pits have been filled in.

Made ground is not necessarily objectionable for building on, especially if it has been accumulated for a long enough time to have consolidated. But where decayed animal and vegetable matter has been shot recently, it is highly objectionable.

Authorities vary very much with regard to **safe pressure** on the various materials of which the ultimate foundation may be composed, and the materials vary very much as to their capability of bearing weight. Hence the engineer should have recourse to the latest text-books, by-laws, etc.

But the following may be taken as an indication of the extent to which safe pressure may vary :—

Loamy soil	0·8 ton per sq. ft.
Soft clay	1·0 ,, ,,
Stiff clay	1 to $1\frac{1}{2}$ tons per sq. ft.
Rocky soil	$1\frac{1}{2}$,, $3\frac{1}{2}$,, ,,
Sound clay or gravel . .	$2\frac{1}{4}$,, 4 ,, ,,
Very firm coarse sand, stiff gravel, or hard clay . .	4 tons per sq. ft.

Rock varies greatly according to composition, etc.

General considerations may be discussed under the heads of (1) Uniformity, including thinning out of beds and varying resistance to pressure; (2) Drainage; (3) Dips; (4) Faults.

Uniformity. For building sites it is most desirable that the

general character of the ultimate foundation or subsoil should be uniform. It is therefore necessary to take into account not only the ordinary variations of the different strata, but also the thinning of beds which often occurs along their outcrops, as well as those due to the shape of the ground.

Another important point to bear in mind is the varying resistance to pressure obtained from different strata, etc. (see above). Hence it is very undesirable to build where strata meet, *e.g.* partly on gravel and partly on loam or other material, or to build near the edge of an old excavation.

Drainage. Springs may be expected under the various conditions shown in figs. 27 to 34. To guard against spring water entering under the floor, the site must be adequately drained, as must also be done if a building is erected on sloping ground, in order to keep out surface-water.

Dips. In preparing a foundation care must be taken to prevent the lateral escape of the soil or movement of a bed that dips, as well as to provide against any damage by the action of the atmosphere.

Faults. It is most objectionable to build on or near a line of fracture, for not only are springs liable to occur, as in figs. 35 to 36, but such faults are liable to further displacement in earthquakes or even slight earth movements.

Rock. Solid rock, extending over the whole area of a building, forms an excellent foundation, provided that it is uniform in character, thick enough to bear the weight of the building, and not liable to be affected by the atmosphere.

It is most desirable that the bedding planes of the rock should be as nearly horizontal as possible, for if they are inclined, there is danger of an upper layer slipping over a lower one. Moreover, the expense in levelling the foundations in steps will be considerable.

Chalk varies very much in its characteristics, in some places being as hard as rock, and in others quite soft owing to the presence of water. The Chalk formation is porous except in its lowest part, and consequently water sinks readily through it, but in hollow places it may become water-logged.

As a rule it affords admirable building sites, but it must be carefully tested to see if there are any cavities or 'pipes' filled partially with gravel or sand. These are not uncommon in the Chalk, and lead to sudden sinking of the soil. Again, when the chalk dips towards a slope or a cliff into an outcrop of the gault or underlying

clay, it is very unstable, and landslips are likely to occur, as happened in the Isle of Wight and on the Dorsetshire coast, etc.

Alluvium or **Marsh Land.** Alluvium (*cf.* Chapter I, Section I) is composed of a mixture of fine materials consisting of sand and mud, often described as 'silt,' and larger materials consisting of gravel in every degree of coarseness; carbonaceous matter is often included, but as a rule there is not much clay.

Marsh lands, and the low-lying lands bordering the lower courses of rivers, are liable to be flooded and, even if protected by banks, are most undesirable as building sites.

When, however, houses have to be built on river flats, basements should be avoided, and the whole area under the floors and walls should be protected by an impervious layer.

Sand forms a good foundation if dry and not liable to be washed away; but this easily occurs: drains with leaky joints may cause a subsidence, or any disturbance of the water-level in the stratum, whether by natural or artificial means, such as pumping operations connected with deep foundations, even at a great distance.

Sand has a tendency to lateral movement, and must therefore be confined by sheet piling or other means. These precautions are still more necessary in the case of quicksands and silt, which are very treacherous soils and will easily yield or slip under slight pressure.

Here, too, it is most important to exclude water which might cause hollows and lead to subsidence. A hollow in clay filled with sand or gravel would probably be charged with a good deal of water.

Gravel. Gravel soils have a high reputation for salubrity, and as a general rule they have undoubted advantages, especially as regards warmth, dryness, and absence from fog, but in low-lying areas they are liable to contain much ground water. Moreover, when foul, they are especially dangerous, as the movements of ground air are much greater in loose, porous soils than in closer ones.

Gravel, when sound, makes an excellent foundation, since it is not affected by the atmosphere and is not compressible. If it is unsound, it may be necessary to act as in the case of loose sand.

Clay affords a good foundation when it is sound, dry, and protected from the atmosphere. It is very liable to crack in hot weather and admit water, when it swells, and the foundations are affected. Clay soil, however, has the objection that it retains moisture for a long time, and thus the health of occupants of build-

ings may be affected. For the above reasons it is essential that thoroughly adequate drainage should be provided.

Gravel on Clay. It is often better to build on a clay subsoil than on a thin gravel or other porous subsoil resting on clay, for the former will absorb only a small proportion of rain-water, throwing off the remainder, while the latter will hold a vast amount of water and act like a sort of tank. Hence, in either case adequate drainage is essential.

Another disadvantage of a thin, porous layer over clay is the liability of contamination of the porous layer from cess-pits, sewage, graveyards, etc.

The **most desirable subsoil** is one that is dry and clean. In rural districts the probable dryness of sites may be ascertained by reference to the position of springs on hillsides and the height of water in wells.

INDEX